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Helmet Electronics & Display System-Upgradeable Protection (HEaDS-UP) Phase III Assessment: Headgear Effects on Auditory Perception

by Angelique A. Scharine and Rachel A. Weatherless

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14. ABSTRACT

Two prototype modular helmet systems were evaluated for their effects on auditory perception. The systems consist of a helmet, eye and mandible protection, and a tactical communications and protection system (TCAPS) that incorporates earmuffs (EM), earplugs (EP), or both. Minor differences in passive directional attenuation were measured for the two systems. The output levels of the situation awareness (SA) microphones of the TCAPS were measured as a function of noise level and amplification setting. It was shown that they limited noise transmission when ambient levels exceeded 85 decibels A-weighted (dB A); however, it was possible to amplify levels at 85 dB A by 20 decibels (dB). The attenuation of 145- and 160-dB peak impulses was measured for the EP and EM with the SA microphones off and when turned on. When the SA microphones were on, the TCAPS provided impulse noise protection equivalent to that of passive protection. When the helmets were worn without mandibles, auditory localization ability was similar to that observed for the Advanced Combat Helmet (ACH). Wearing the mandible caused significant decreases in localization ability. Listeners wearing the TCAPS system showed no impairment of recognition for speech presented in quiet as compared to unaided listening.

15. SUBJECT TERMS

hearing protection, level dependent, sound localization, attenuation, noise, headgear, mandible directional effects

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1. Introduction

This effort was conducted through the Helmet Electronics & Display System-Upgradeable Protection (HEaDS-UP) Program to characterize the acoustics effects of two helmet and hearing protection systems in impulsive and continuous noise environments. There were two objectives for this testing. The first, was to document the protection provided against noise-induced hearing loss, specifically from steady-state and impulsive noises. The second, was to document the effects of these two systems on hearing capabilities, specifically on the ability of a user to detect, recognize, and localize ambient environmental and speech events.

Figure 1 shows the two candidate helmets, each designed to be used with a detachable mandible, eye protection, and the SELEX* tactical communications and protection system (TCAPS). The first helmet candidate (figure 1a), the INTEgRated Conformal Protective helmeT (INTERCPT), was developed by Revision Military. The second candidate (figure 1b), the Conformal Integrated Protective HEadgeaR (CIPHER), was developed by Artisent LLC†. The TCAPS components include (figure 1c) circumaural earmuffs (EM) and (figure 1d) in-the-ear (ITE) earplugs (EP) that can be worn independently or in combination as double hearing protection. The CTX communications hub (figure 2) provided by SELEX Communications allows the user to switch between radio-only and radio-plus situation awareness (SA) microphones. The CTX also has inputs for either EP or EM headsets and is wired to allow them to be used jointly in cases where double hearing protection is required.

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* SELEX Communications, Inc is a SELEX Elsag Company, part of the Finmeccanica Group and has offices in Washington, DC and Reston, VA.

† Artisent LLC is a subsidiary of Gentex Corporation located in Boston, MA.
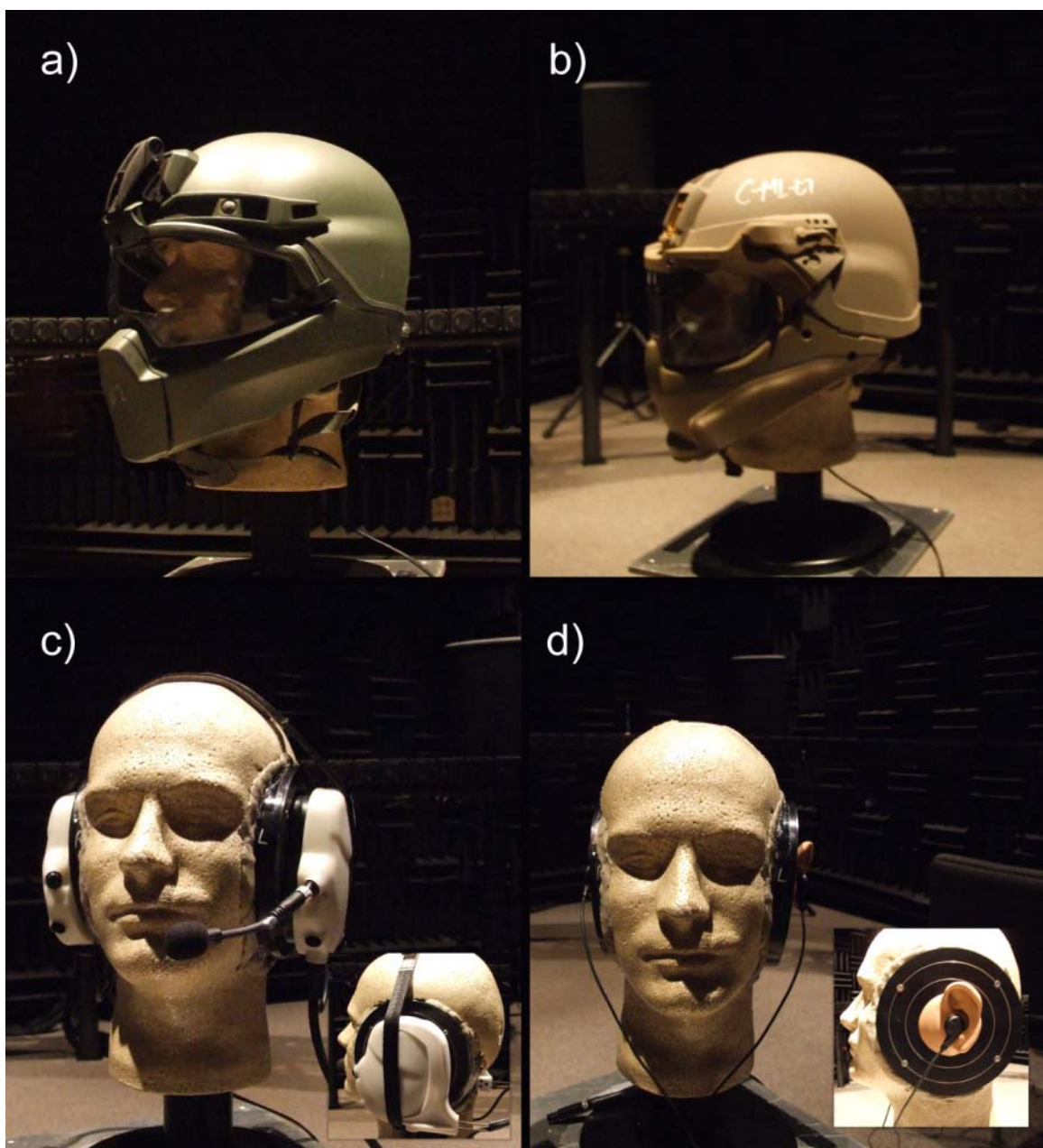
Figure 1. System components tested: (a) INTERCPT helmet, (b) CIPHER helmet, (c) EM, and (d) EP.

Figure 2. SELEX CTX communications hub.

The SELEX TCAPS serves as a hearing protection device (HPD) by providing passive and active protection against unsafe levels of noise. Passive protection comes from the attenuation created by the EM or EP as a barrier to prevent transmission of sound. Although the attenuating effects of the helmets are minimal, they alter the spectral profile of the sounds reaching the ear. HPDs also alter the physical profile of the region near the ears and passively attenuate incoming sounds, reducing overall sensitivity.

Auditory SA can be restored when the HPDs are turned on, as the external SA microphones transmit ambient sounds to the ear. Active protection against noise-induced hearing trauma is provided by electronically limiting sounds above approximately 85 decibels A-weighted (dB A), and a shutoff is triggered by impulsive noise. However, the SA microphones may not transmit frequencies above 8 kHz, which is sufficient for speech communication, but could potentially reduce detection of certain environmental sounds and alter the spectral information available for localization.

Therefore, our testing included measures of passive directional attenuation of the HPDs and helmets. We also measured the input-output function of the SA system to determine when the hearing protection components engaged in response to steady-state noise. Measurements were made for two levels of amplification and two levels of ambient noise in order to determine the sound pressure levels under the HPD as a function of these variables.

HPDs with active SA microphones must shut off transmission quickly in response to impulsive noises such as weapon fire. Measurements were made of HPD attenuation with the SA system turned on (active), and with them off (passive) to ensure that the systems are protecting adequately against noise when the SA microphones are turned on.

Because the spectral cues used for sound localization are distorted by directional passive attenuation and possibly the SA microphone's spectral transmission characteristics, we measured the localization performance of 11 participants while wearing various combinations of the helmet/HPD systems.

To demonstrate the performance of the SA microphones for face-to-face speech communication, we measured the speech recognition performance of six participants listening to speech items presented at three loudness levels.

1.1 Directional Passive Attenuation and Situation Awareness Microphone Transmission

The placement of a helmet or HPD over the ears will passively attenuate ambient sounds. In order to describe the effects of the helmets and HPDs on auditory sensitivity, passive directional attenuation was measured for EM, EP, double hearing protection, and each of the helmets—worn both alone and with EP.

The HPD and SELEX communication hubs are designed to compensate for the passive attenuation of the helmet and HPD and to provide SA via microphones located on the EM that transmit ambient sounds to the earphones in the device. When the ambient noise levels are below dangerous levels (approximately 85 dB A [OSHA, 1981]), these systems allow the user to hear ambient communication and environmental sounds as if the ears were unoccluded. When ambient noise levels exceed 85 dB A, the system limits or compresses the transmitted level, thus protecting the user. The actual level under the hearing protection device depends, however, on the amount of noise that is not passively attenuated by the hearing protection device as well as the level of amplification selected by the user. Therefore, a second test was conducted to ensure that the SA microphones of the EM and EP were attenuating unsafe levels of noise. For this test, the level of sound under the HPD was measured as a function of presentation level (70–105 dB A) and the amplification setting of the SA feature (e.g., off, on-low, on-high).

1.1.1 Facilities and Instrumentation

1.1.1.1 Auditory Test Fixture (ATF), Reference Microphone, and Recording System.

During both the measures of directional passive attenuation and the SA microphone transmission a G.R.A.S.[*] Hearing-Protector Test Fixture Type 45CA, fitted with IEC 60711 ear simulators and molded pinnae, was positioned in the center of the room and was used to record the test signal. This ATF is not meant for testing helmet attenuation—it was designed for hearing protectors. It was modified to create a head shape by cutting a hole to the shape of the ATF in the center of a Styrofoam[†] manikin head. The ATF was then protected using a layer of cellophane wrap and inserted into the manikin head. The head was then sealed to the ATF using thumbgum (see figure 3). A PreSonus Firestudio[‡] recording interface, set to a sampling rate of 44.1 kHz was used for analog-to-digital conversion and to transmit the signal to a laptop computer, where it was recorded using Adobe Audition 3.0.

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[*] G.R.A.S. Sound and Vibration is a Danish company that manufactures high-quality microphones.
[†] Styrofoam is a registered trademark of the Dow Chemical Company.
[‡] PreSonus Firestudio is a registered trademark of PreSonus Audio Electronics, Inc.

When measuring the SA microphone transmissions, a G.R.A.S. 40 BH microphone was used to make reference recordings of the signal levels. This allowed minor variations in signal level to be corrected in the data.

Figure 3. Modifications of the G.R.A.S. 45 Hearing-Protector Test Fixture Type CA used to accommodate helmet testing. Left: the ATF inserted into the manikin head. Right: View with thumb-gum used to seal the manikin to the ATF.

1.1.1.2 Research Facilities, Loudspeaker, and Test Signal

Directional Passive Attenuation. A pink noise test signal was presented from a JBL PRX512M loudspeaker located in the corner of the U.S. Army Research Laboratory's (ARL) Environment for Auditory Research (EAR) Dome Room (Henry et al., 2009), about 3.5 meters (m) from the center of the room. The noise was presented at 100 dB A as measured with a Brüel & Kjær Sound Level Meter Type 2226 held at the location of the ATF. This level was chosen because it is within the range for which the microphones (inside the ears) of the ATF are designed and high enough to remain in that range when an HPD is in place. The EP and EM were tested with the SA microphones turned off.

SA Microphone Transmission. During the second test, a white noise test signal was presented from four JBL PRX512M loudspeakers located in the Listening Laboratory of the EAR (Henry et al., 2009) facility (figure 4). Two panels were removed from each wall of the room to increase reverberation time and to create a diffuse sound environment. A Bruel & Kjaer Type 2226 sound level meter (SLM) mounted on a tripod was used to measure the sound levels in the room. The

test signal was adjusted until the SLM (A-weighted/slow setting) matched one of eight target levels (70, 75, 80, 85, 90, 95, 100, and 105 dB A).
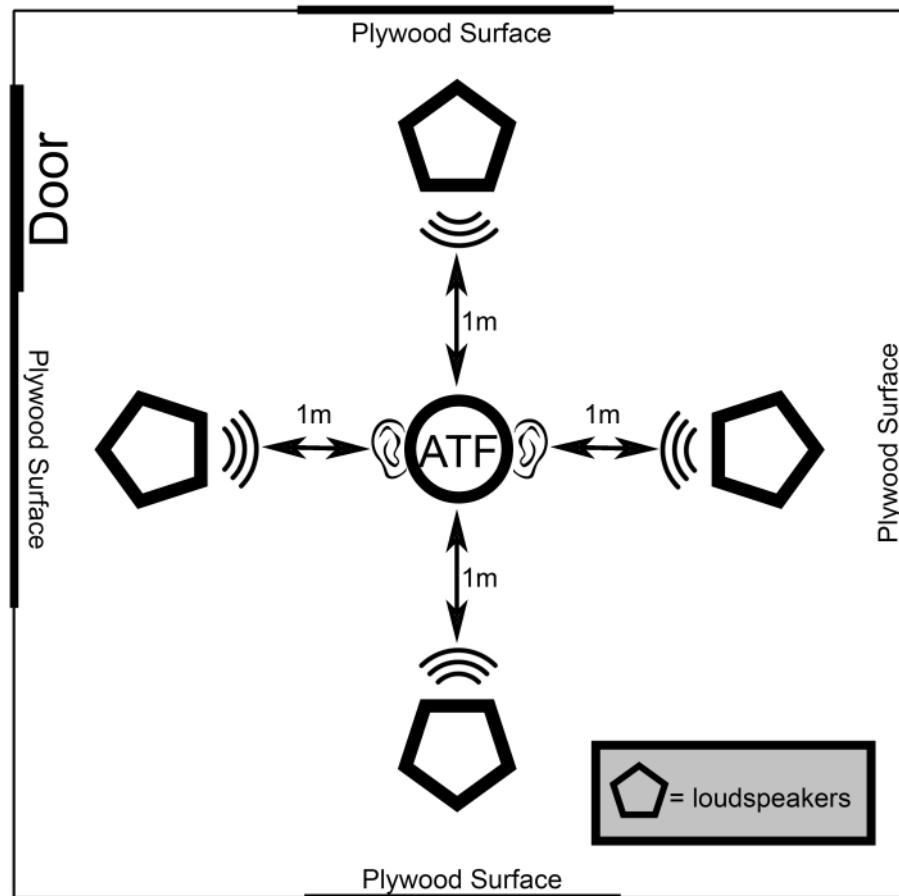
Figure 4. Schematic depicting the Listening Laboratory and the configuration of the loudspeakers and the ATF during the measurement of steady-state noise attenuation.

1.1.2 Independent and Dependent Variables

Directional Passive Attenuation. There were three independent variables investigated in the first test: helmet/HPD condition, azimuth angle (0°, ±30°, ±60°, ±90°, ±120°, ±150°, 180°), and frequency. The helmet/HPD conditions were: CIPHER, CIPHER + EP, INTERCPT, INTERCPT + EP, EM, and double hearing protection. The dependent variable was attenuation, defined as the difference between the signal level, as measured by the ATF, with and without the helmet/HPD.

SA Microphone Transmission. The dependent variable in the second test was the level (dB A) as recorded by the ATF under the HPD as a function of the independent variables, presentation level (70–105 dB A) and active gain setting (off, on-low, and on-high). Measurements of the dependent variable were made for all levels of the independent variables for the EM. Since the CTX communications hub contains the electronics responsible for controlling the transmission of

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sound via the SA microphones, the EP were tested in only the off and on-low amplification settings as a verification of this fact.[*]

1.1.3 Procedures

A G.R.A.S. 42AA sound calibrator with an adapter that allows it to be coupled to the ATF was used to generate a signal of 250 Hz at 114 decibels (dB). This signal was recorded through each channel (left and right ears) of the testing system and provided a calibrated reference for the later recordings. The reference microphone used for the SA microphone transmission measures was calibrated using the same calibrator (using a standard 1/4-inch [in] coupler).

Passive Directional Attenuation. The 100-dB sound pressure level (SPL) pink noise test signal was played continuously from the loudspeaker. Recordings of 5-second (s) duration were obtained from the microphones in the ATF in one of the seven angular orientations in the right hemisphere. In between recordings, the experimenter rotated the ATF in order to position it in one of the seven orientations. This process was completed once without headgear and twice[†] for each of the helmet/HPD conditions.

For the first test the bare head ATF recordings served as reference measurements for each of the helmet/HPD conditions. Figure 5 shows the position of the loudspeaker and the angles used. Although sounds were only presented from the right hemisphere relative to the ATF, it is reasonable to assume symmetry between ears. Therefore, since recordings were made from ATF ears (left and right channels) simultaneously, we can assume that the measurement taken from the left ear when the ATF "nose" is pointed to +30° is approximately the same as would be obtained from the right ear when the ATF "nose" was pointed to -30°. Therefore, with each noise presentation, we obtained directional attenuation data for a pair of angles (0°, ±30°, ±60°, ±90°, ±120°, ±150°, 180°) allowing us to represent directional attenuation for the full 360° horizon. These measurements were repeated in order to account for variability due to fitting the helmet/HPD and resulted in two data points for each angle (four at 0° and 180°).

SA Microphone Transmission. To obtain the noise levels under the HPD, the ATF was fitted with the HPD, the gain was set to one of the active SA settings (off, on-low, on-high), and the noise output was adjusted until the SLM (using A-weighting and slow response) showed the target level (70, 75, 80, 85, 90, 95, 100, and 105 dB). A 10-s recording was made. This process was repeated for each of the target levels and active SA settings until the recordings were complete.

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[*]While it is true that the SELEX CTX communications hub controls the electronics that provide hearing protection, there are enough differences in the passive attenuation provided by the earmuffs versus the earplugs to warrant full testing at both amplification settings. A full set of measurements is planned for Phase IV of this project.

[†]The reason for two measurements for each of the headgear conditions was to gain estimates of variability due to fitting inconsistency.
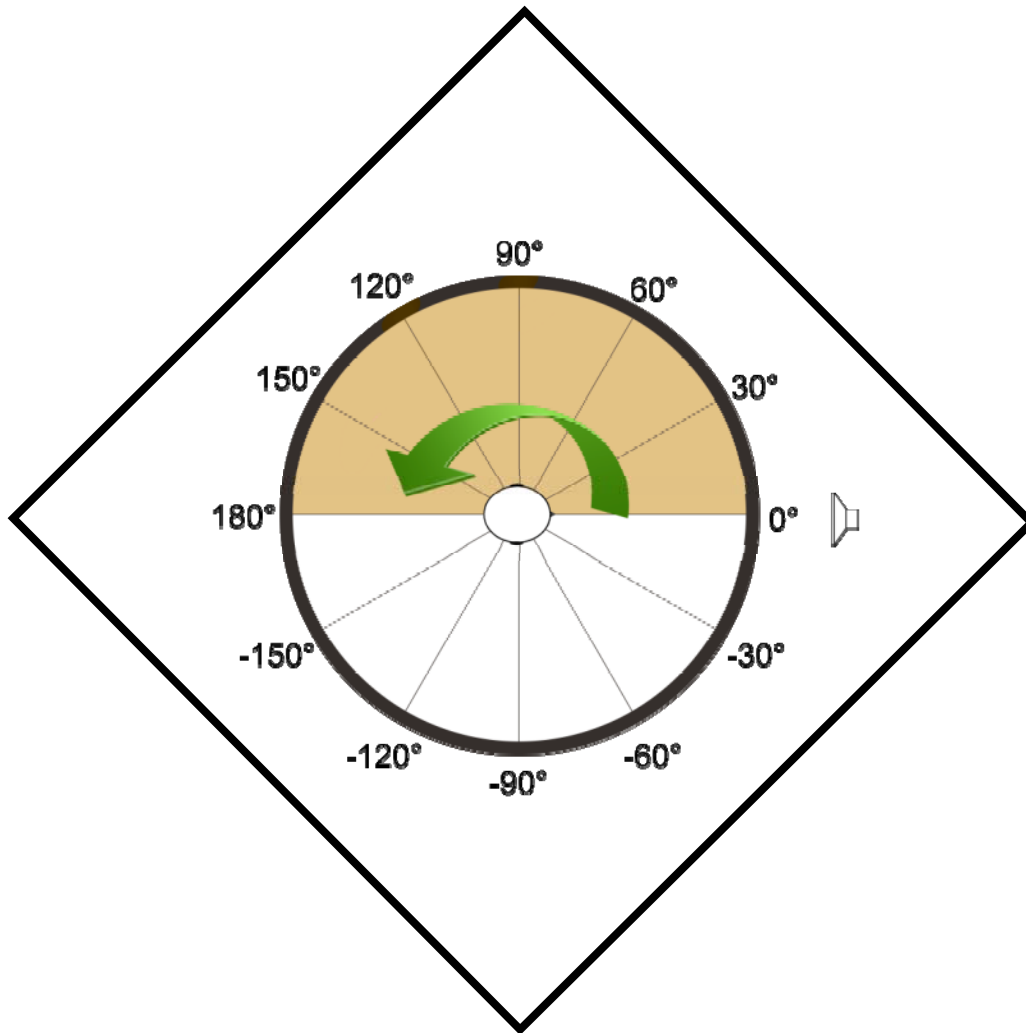
Figure 5. Schematic of test setup used for the continuous noise attenuation measurements. The ATF was rotated, in 30° increments to each of the positions indicated by the markers in the shaded region.

1.1.4 Data Analysis, Results, and Discussion

1.1.4.1 Passive Directional Attenuation

Each set of directional recordings (2 × helmet/HPD × azimuth angle) was processed using a custom MATLAB[*] algorithm to compute the levels for each component octave and one-third octave band (ANSI/ASA S1.6-1984 [R2011]). This was also done for the reference set recorded with no helmet/HPD. A-weighting (ANSI/ASA S1.42 [R2011]) was then applied and the A-weighted one-third octave, octave, and overall levels were obtained. A-weighted values were used for all analyses reported here. For each helmet/HPD, directional attenuation was calculated by computing the reduction in the overall A-weighted signal level when the device was in place compared to the level in the bare fixture. Attenuation, as a function of one-third octave and octave band frequency was then calculated in the same manner. Directional attenuation (figures 6

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[*] MATLAB is a registered trademark of Math Works Inc.

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and 7) is shown as a function of the orientation of the ATF "nose" with respect to the loudspeaker as measured from the right ear of the ATF. Figure 8a shows the same data for the HPDs and figure 8b shows the helmets with the error bars representing ±1 standard deviation.
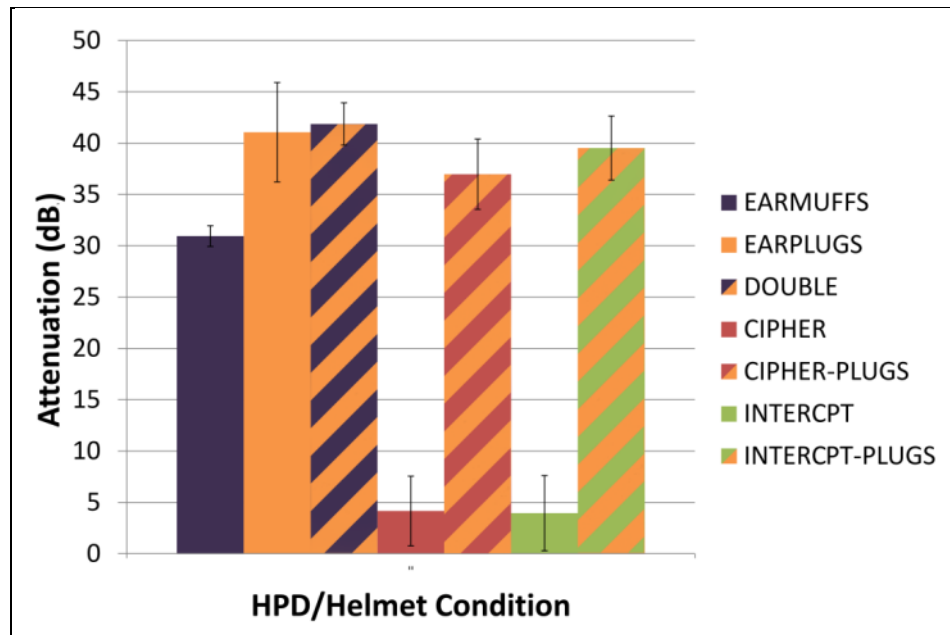
Figure 6. Average overall attenuation measured for each of the helmet/HPD conditions. Error bars represent ±1 standard deviation.
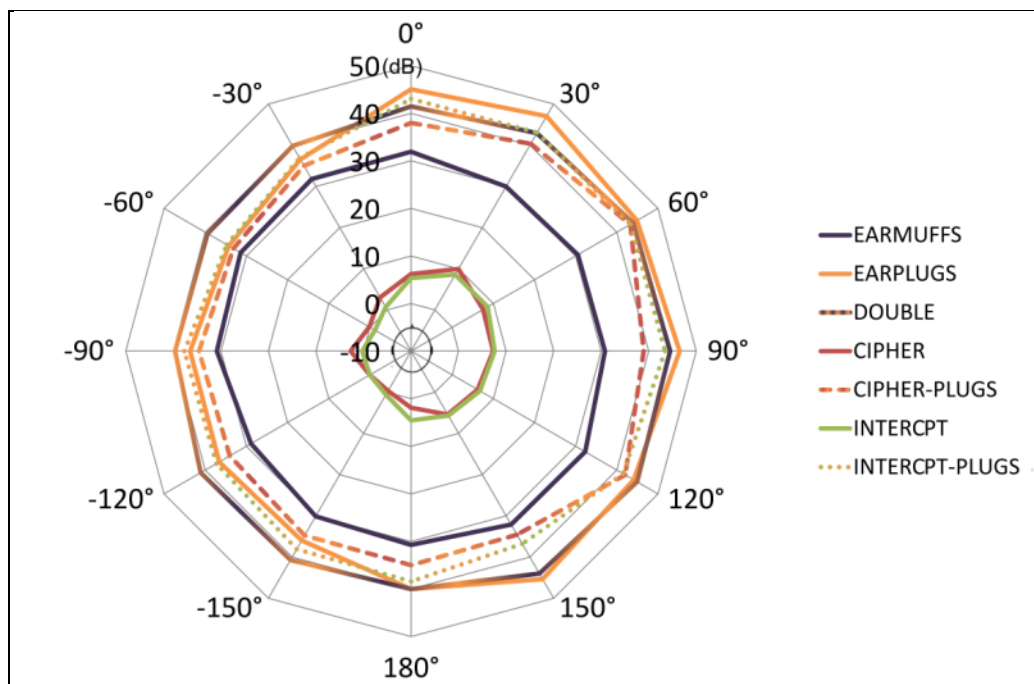
Figures 7. Overall directional attenuation as measured for the helmets and hearing protection. In this graph and subsequent graphs, the angles represent the orientation of the ATF's nose relative to the loudspeaker position. The values represent the attenuation measured from the right ear of the ATF relative to the bare head condition.
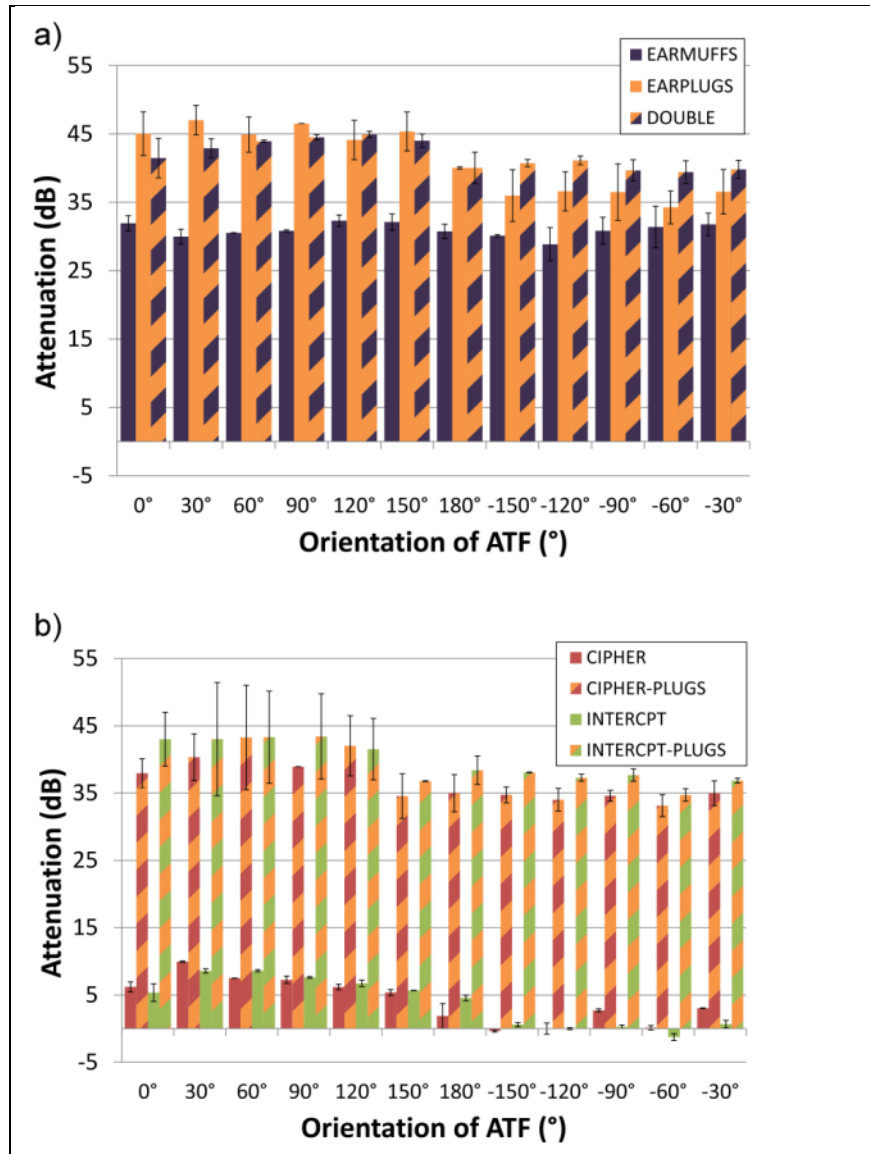
Figure 8. Directional attenuation for (a) hearing protectors and (b) helmets. Error
bars represent ±1standard deviation (variability due to fitting).

1.1.4.2 Broadband Directional Attenuation

It is clear that the helmets themselves attenuate very little and their effects do not differ from
each other. There is some evidence of a slight amplification of sounds at some angles. Most
likely, the sounds reflect from the inner surface of the helmet causing delayed summing. This
effect is minimal, usually less than 1 dB. Greater attenuation was observed for the earplugs as
compared with the earmuffs. This is consistent with typical[*] noise reduction rating (NRR) data
for EM and EP. Double hearing protection provided only slightly more overall protection than

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[*]The NRR for the 3M Peltor ComTAC (a similar tactical EM) is 22 dB. The NRR for the Comply Foam tips used with the EP
has an NRR of 29 dB.

for the single EP condition. This is consistent with the findings of Berger (1984), who compared the attenuation of deeply inserted foam EP and that of the same EP combined with an EM and found that they increased the NRR by 4 dB. Here, it is also likely that the wires from the EP introduce leakage when they extend from the EM.

1.1.4.3 One-Third Octave and One-Octave Directional Attenuation

Figure 9 shows the helmet/HPD attenuation as a function of one-third octave band frequency for four angles (0°, ±90°, and 180°).[*] Note that much of the minimal attenuation observed for the helmets alone occurs in the frequency range above about 1000 Hz. These higher frequencies (>3 kHz) contain the monaural and interaural level difference cues that are responsible for localization, especially for distinguishing sounds from the front from the rear and estimating elevation. For three of the angles, a peak in amplification can be observed for the CIPHER helmet near 300 Hz, such that sounds are amplified by 5–8 dB. At around 450 Hz the CIPHER helmet seems to show a local notch in amplification, whereas the INTERCPT helmet shows a peak—amplifying sounds by approximately 5 dB at some point between about 450 and 800 Hz, depending on the angle of incidence.

For all helmet/HPD conditions there is some variability in the attenuation achieved at the one-third octave level of resolution that may drive differences in subjective estimates of performance and localization effects. Figures 10–13 show the attenuation of the helmet/HPD conditions at one-octave band resolution as a function of direction. In these graphs the convention is that dashed lines represent attenuation measured for the left side and dots represent 180°.

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[*] Note that for the directional passive attenuation measurements, there are two possible ways to describe the data: (1) the orientation of the ATF nose, or (2) the position of the loudspeaker with respect to the microphone ear. The data were originally collected and labeled with respect the position of the loudspeaker (2), but for graphing purposes we reported the data as a function of ATF orientation. This resulted in the right hemisphere being labeled as negative and the left one as positive. This is the reverse of the labeling used for the localization data.

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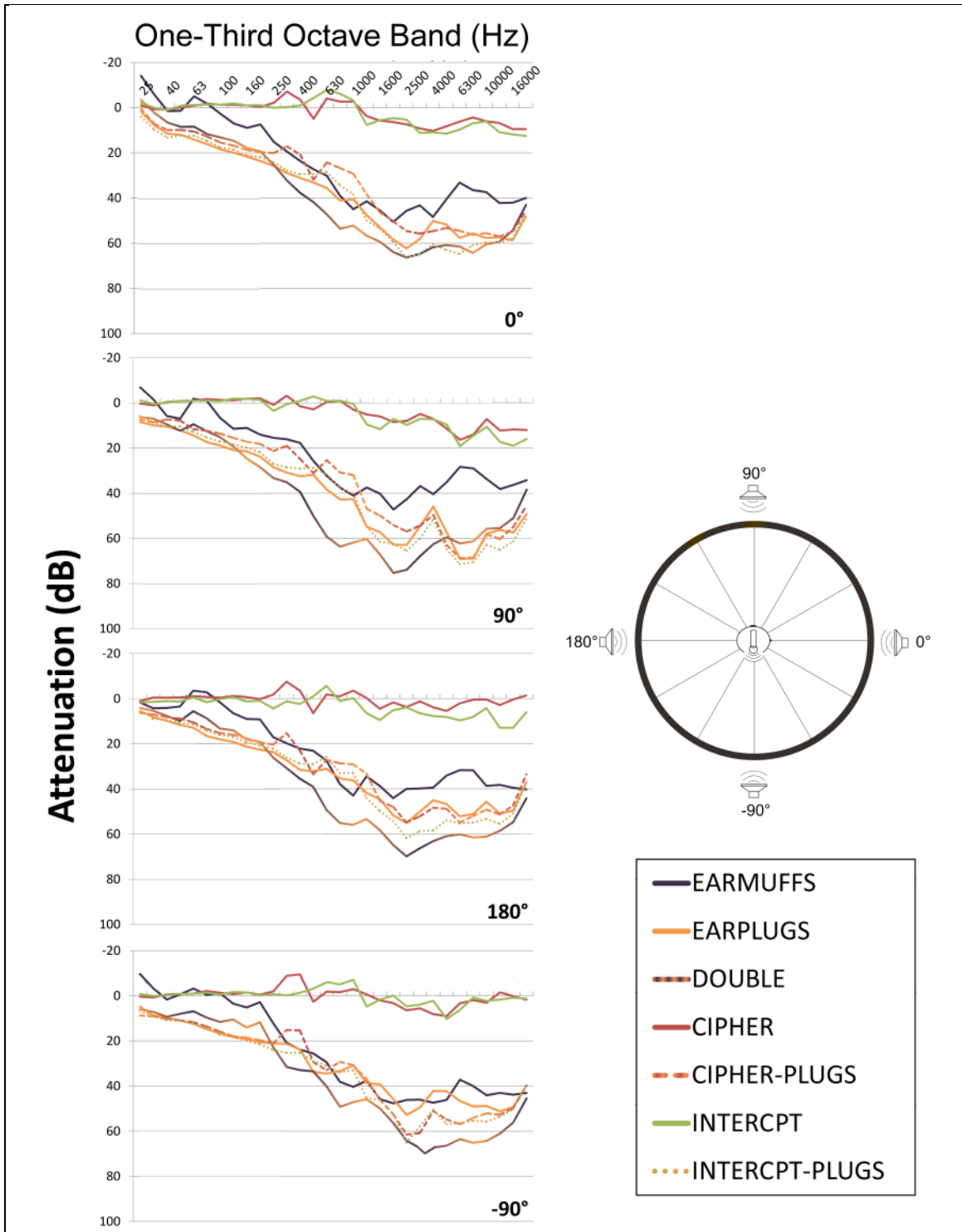
Figure 9. Attenuation of each helmet and hearing protector shown as a function of one-third octave frequency band for four angles. The schematic indicates the relative position of the loudspeaker with respect to ATF ear and microphone for each of the graphs shown.

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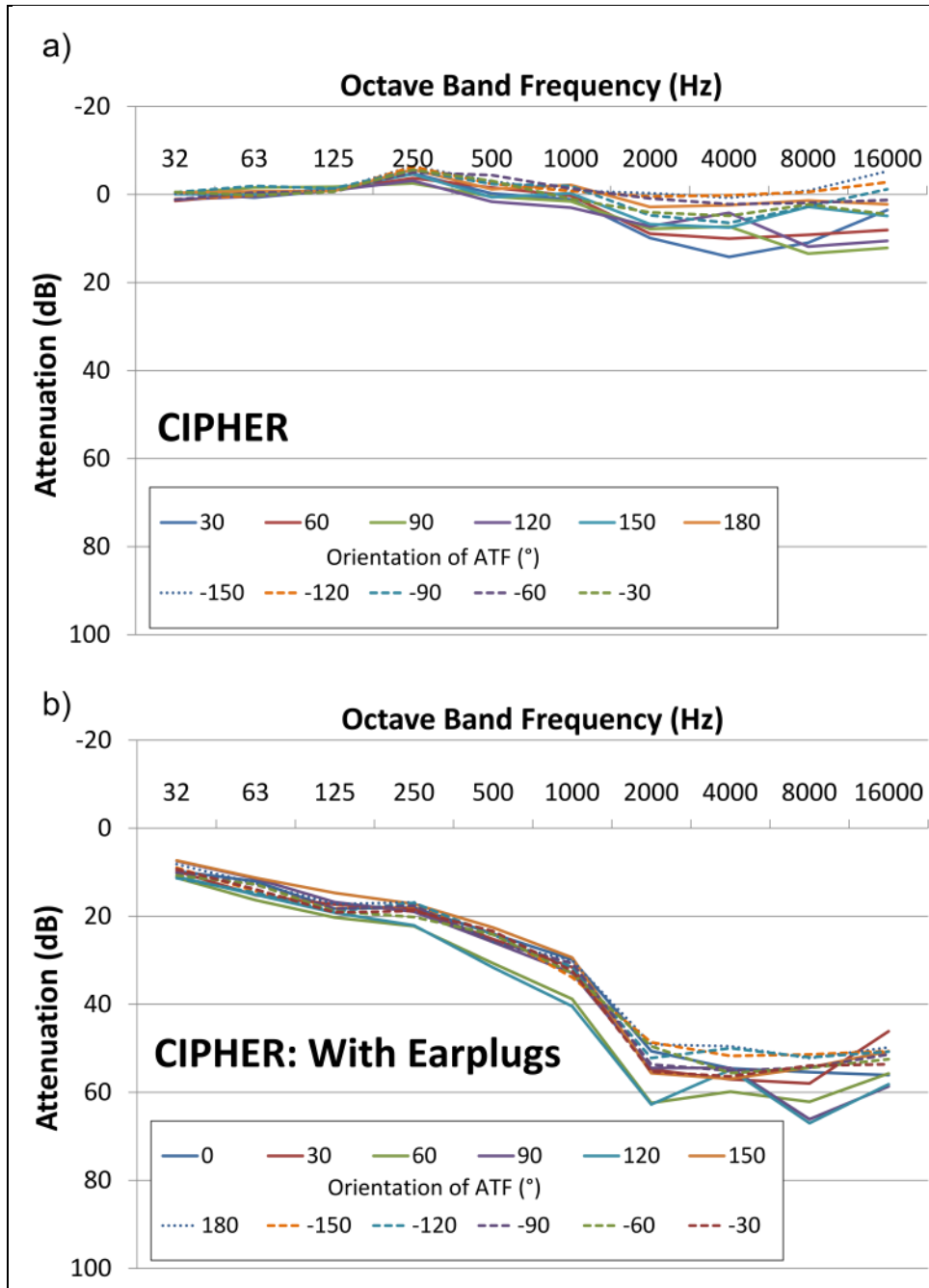
Figure 10. Attenuation as a function of octave band frequency and ATF orientation for the (a) CIPHER and (b) CIPHER + EP conditions. (In figures 10–13 the convention is that dashed lines represent attenuation measured for the left side and dots represent 180°.)
Note: In these graphs and those of the next three figures, the convention is that dashed lines represent attenuation measured for the left side and dots represent 180°.
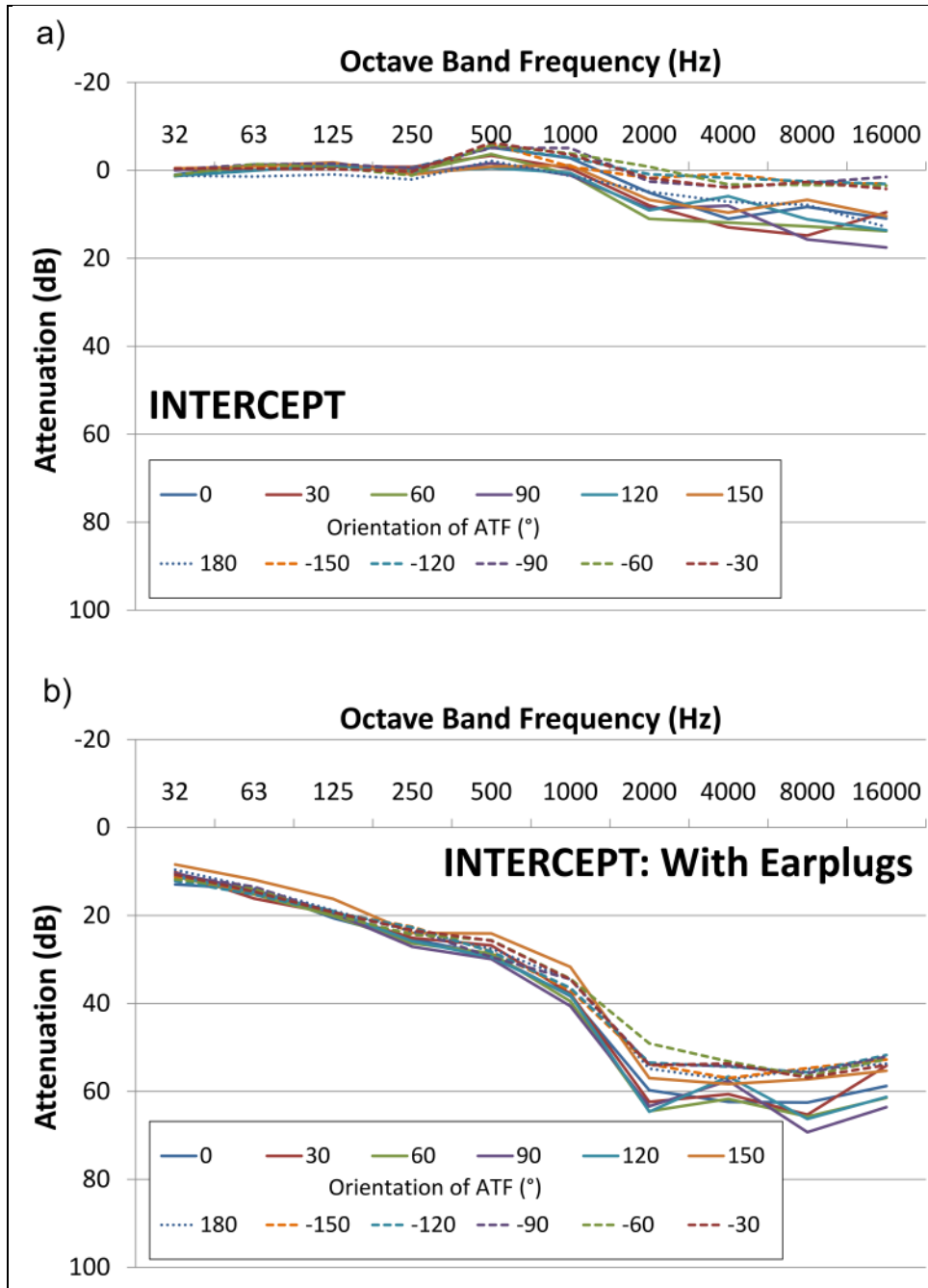
Figure 11. Attenuation as a function of octave band frequency and ATF orientation for the (a) INTERCPT and (b) INTERCPT + EP conditions.
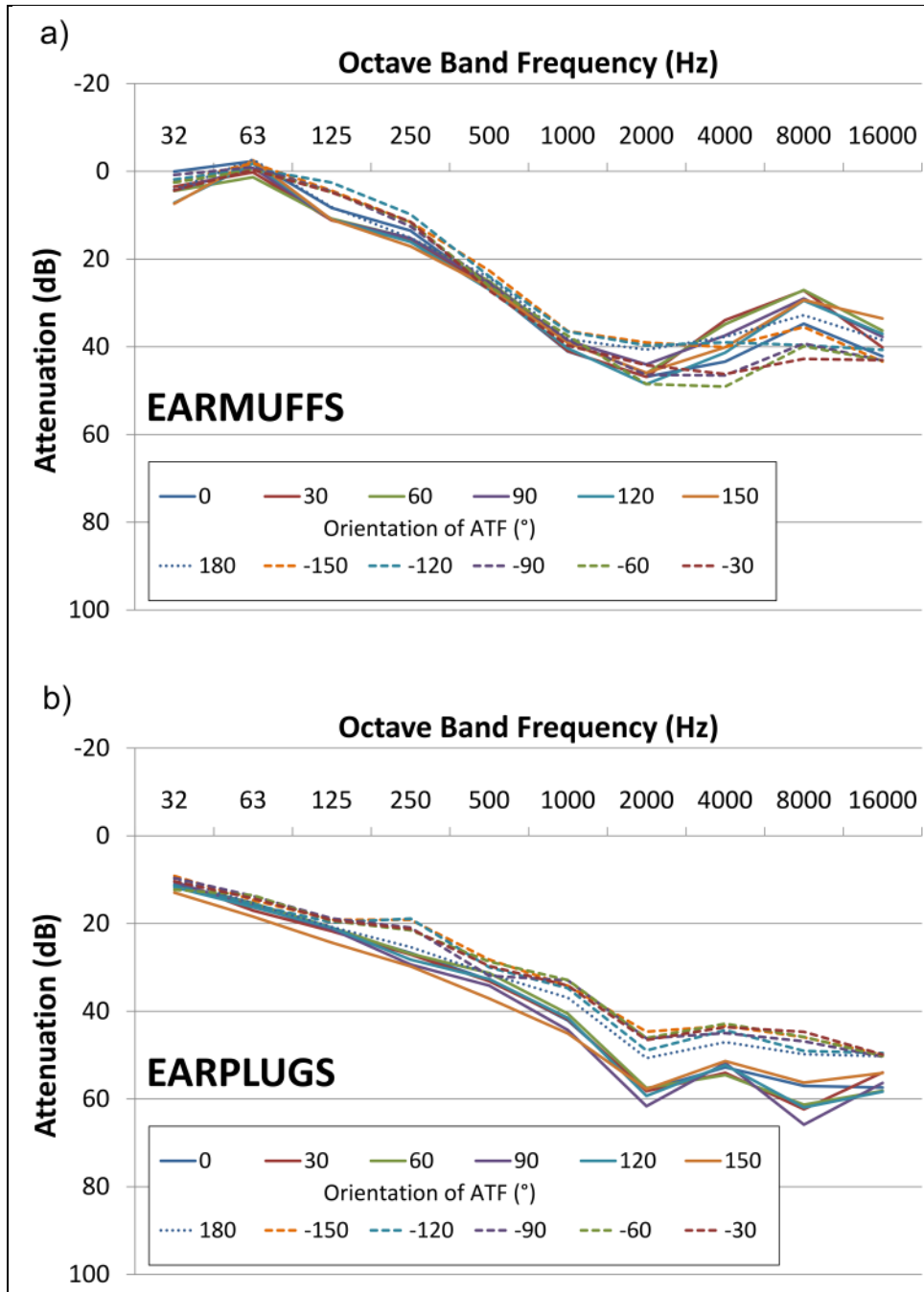
Figure 12. Attenuation as a function of octave band frequency and ATF orientation for the (a) EM and (b) EP conditions.
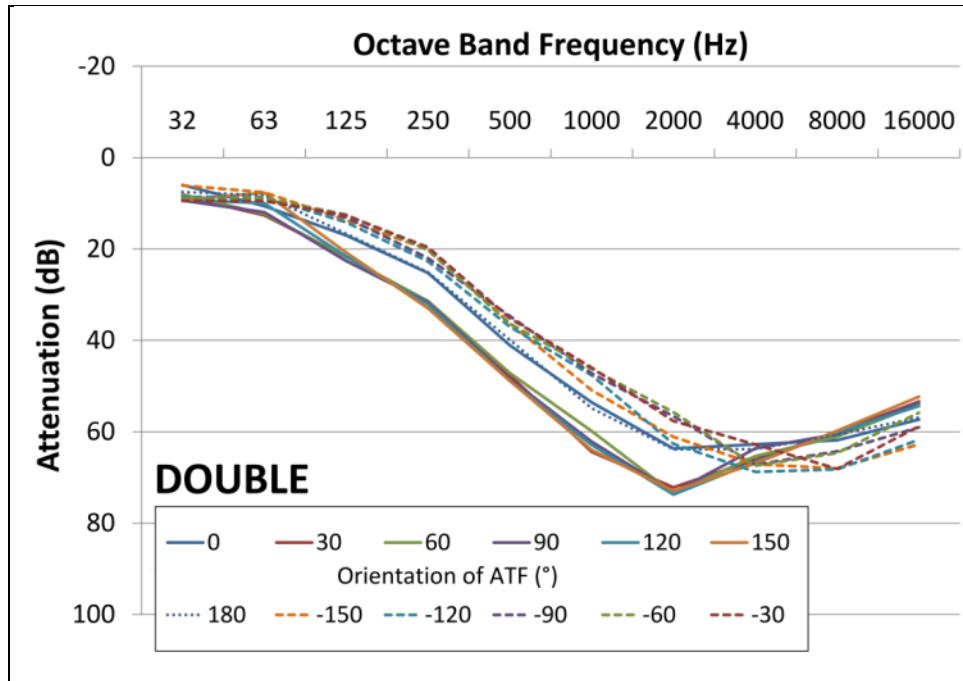
Figure 13. Attenuation as a function of octave band frequency and ATF orientation for the double (EM + EP) condition.

1.1.4.4 SA Microphone Transmission

Because there were minor variations in the actual target levels achieved (as recorded by the reference microphone), the data reported here have been adjusted by correcting the levels measured by the ATF by the difference between the target signal level and that measured by the reference microphone (target signal level = 85 dB A, reference microphone level = 84.8 dB A, reported data = ATF level + 0.2 dB A).

Figure 14 shows the measured levels for the EM and EP for each measured active SA setting and each level of noise. Examining the levels recorded with the HPDs in the passive, off condition, one should note that due to the noise floor of the microphone sensitivity, the minimum level recorded was approximately 60 dB.[*] It is likely that the true levels are lower and the actual attenuation for the earmuffs is about 20 dB, as the measured level begins to increase when the presentation level exceeds 80 dB A. Similarly, the attenuation of the earplugs is approximately 35 dB, as the measured level begins to increase when the measured level exceeds 95 dB A. When the SA microphones are turned on, the noise level at the eardrum increases linearly as a function of the presentation level until the safety shutoff is triggered (at 85 dB A for the earplugs on-low setting). It appears that the difference in level between the on-low and on-high settings is approximately 20 dB. When the SA microphones are set to on-low, hearing restoration is approximately 1:1, in that the external level is restored to the same level as when not wearing

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[*]Ideally, an ATF that allows for the measurement of levels below 60 dB should be used for this measurement. This issue should be resolved in the future Phase IV of testing.

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hearing protection. When they are set to on-high, the restoration is approximately 4:1, so that the level is approximately four times as loud—using the convention that a 10 dB increase in level is perceptually twice as loud (Moore, 2012).
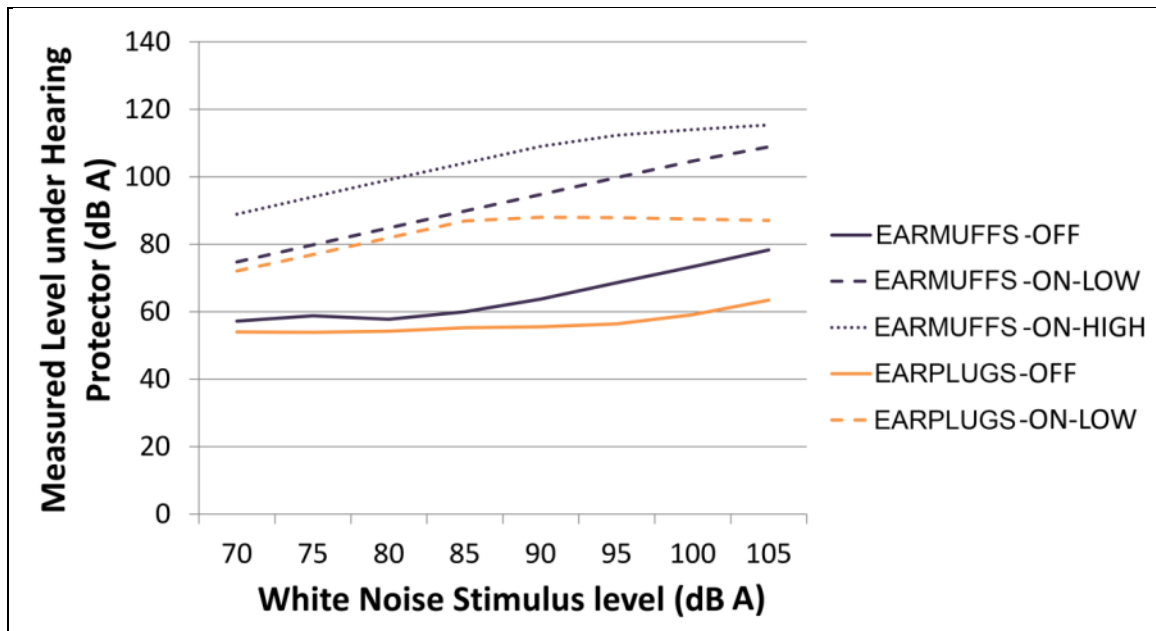
Figure 14. Input-output levels of HPDs as a function of active SA setting and presentation level.

Most active hearing protectors advertise safety limits of 85 dB A, consistent with Occupational Safety and Health Administration (OSHA) (1981), National Institute for Safety and Health (NIOSH) (1998), and Military Standard (MIL-STD) (MIL-STD-1474D, 1997) requirements for hearing protection, for levels at or above 85 dB A. Based on the input-output on-low function measured for the EP, when the ambient noise level exceeds 85 dB A, the level transmitted to the user is reduced to approximately 85 dB A. It might appear that the EM do not do this. However, since the passive attenuation remains constant, the level of noise under the headset not passively attenuated will increase at the same rate as the level of the ambient noise—in addition to the level of noise transmitted by the SA system. Similarly, when the amplification of the SA microphones is set to a higher level, it is likely that inputs are amplified by the same amount until the ambient noise reaches 85 dB A, reaching approximately 105 dB A under the headset. At ambient levels above 85 dB A, the level of noise transmitted by the headset remains flat, but the level of noise not passively attenuated continues to increase and therefore the overall level increases. As the level of ambient noise increases, there appears to be nonlinearity in the system; as the input-output function for the EM in the on-high setting appears to asymptote at about 115 dB A and there is a similar flattening for the EP for the on-low setting for ambient levels above 85 dB A—despite a small increase of noise not passively attenuated.

Does this mean that these systems are not providing adequate hearing protection for steady-state noise? MIL-STD-1474D (1997) specifies hearing protection when a device generates steady-

state noise at or above 85 dB A without regard to the duration of exposure. However, OSHA (1981) and NIOSH (1998) both base their requirements on an 8-hour (h) time-weighted average[*] and are intended for steady-state industrial noise conditions. Speech may be considered as more similar to impulsive noise. Because of the brief duration and somewhat impulsive characteristics of speech, occasionally exceeding 85 dB A when in relatively quiet conditions is probably safe and may be helpful. If a Soldier has sustained a permanent or temporary threshold shift, the on-high SA setting may be necessary for speech communications. However, in noisy conditions, amplification will not aid speech recognition for a normal-hearing user, and will make it worse for a hearing-impaired user, because both the speech and the noise will be amplified (Moore, 2012). Further, most normal-hearing listeners would find amplification of steady-state noise uncomfortable and desire to turn it off. To avoid misuse by users who might ignore the discomfort due to desired improvement in hearing capability and misunderstanding of the safety features, users should be trained to turn off SA microphones when steady-state noise (e.g., vehicle or generator noise) exceeding 85 dB A is present as the SA microphones will cease to aid communication.

2. Impulsive Noise Attenuation

We tested the EM and the EP for their attenuation of impulsive noise. Both devices were tested with the SA microphones set in the off and on-low positions and with impulse levels of 145-dB peak and 160-dB peak. Impulse attenuation of a 160-dB peak noise was also measured for double hearing protection with the SA microphones turned off (noise levels warranting double hearing protection would make the use of the SA system undesirable).

2.1 Facilities and Instrumentation

2.1.1 ATF, Reference Microphone, and Recording System

All impulse noise measurements were made in the Distance Hall of EAR. Recordings were made using the French-German Research Institute of Saint-Louis (ISL) ATF designed to accommodate pressure levels of up to190-dB peak (Buck and Parmentier, 1999). Recordings were made using the same reference microphone and PreSonus Firestudio system described in section 1.1.1. The reference microphone and ATF were 1 m apart at the same distance from the shock tube (figure 15).

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[*]OSHA and NIOSH standards refer to an 8-h A-weighted average and provide exchange ratios for the computation of limits for shorter time frames (Melzer et al., 2012). Depending on the standard, the maximum level can be increased by 3–5 dB if the exposure time is halved. That is, with a 5-dB exchange ratio, if the duration is only 4 h, the maximum level is 90 dB.
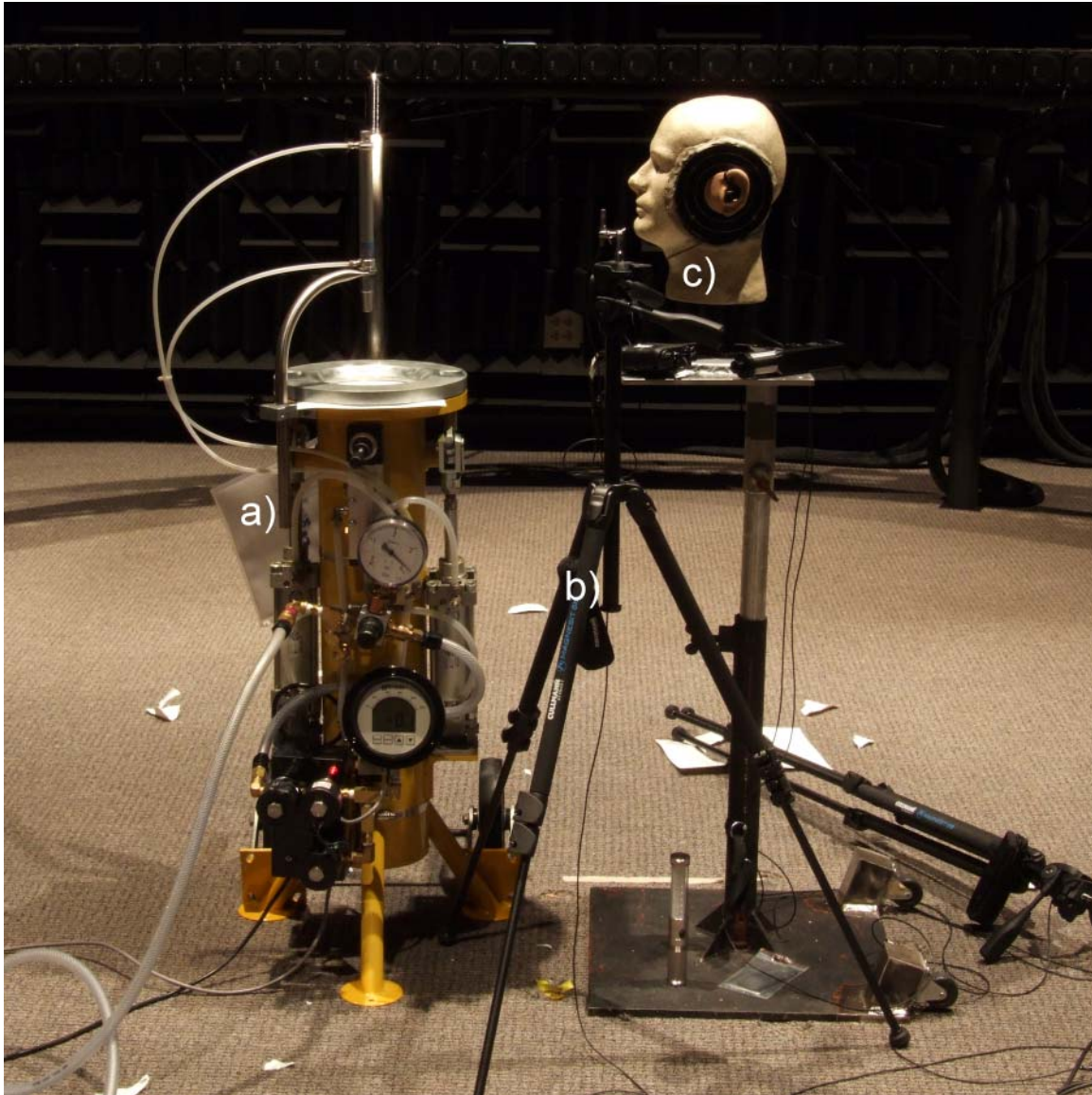
Figure 15. The measurement setup for impulse noise measurement: (a) pneumatic impulse noise source (PINS) shock tube used to generate impulsive noises, (b) G.R.A.S. 40BH reference microphone, and (c) G.R.A.S. 45CA auditory test fixture used to record noise levels.

2.1.2 Impulsive Noise Signal

PINS[*] was used to present impulsive noises for measurement. By adjusting the distance between the shock tube and the microphones from 4 m to 1 m, we were able to reliably generate impulses that measured 145- and 160-dB peak.

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[*]Also known as a shock tube.

2.2 Calibration

The G.R.A.S. 42AA sound calibrator was used to present a 114 dB, 250-Hz calibration signal to the ATF microphones and to the G.R.A.S 40BH reference microphone to establish reference levels. Simultaneous recordings were made of two instances of impulsive noise using the microphones of the ATF (unoccluded ears), and the reference microphone. These recordings were used to estimate the transfer function of the ear canal. From these recordings it was determined that the left and right ears of the ATF contribute amplifications of 4.87 and 4.68 dB, respectively, due to resonance in the ear canal (Shaw, 1974). Attenuation was computed as the difference between the peak level measured by the ATF (the attenuation of the left and right ear were calculated as separate data points) and the peak level measured by the reference microphone, minus the transfer function for that ear.

2.3 Testing Procedure

The HPD was positioned on the ATF and a recording of the shock-tube generated impulse noise was obtained from the microphones of the ATF and the reference microphone. This process was repeated three times for each HPD (EM, EP, and both) in each SA microphone condition (off and on-low). The HPD was removed and refitted between each measurement.

2.4 Data Analysis, Results, and Discussion

Three impulsive noise signals were presented for each HPD and SA microphone setting, resulting in six attenuation values. Average attenuation of an impulse signal of 145-dB peak (figure 16a) and 160-dB peak (figure 16b) was computed for each HPD at each SA microphone setting. The error bars represent ±1 standard deviation.
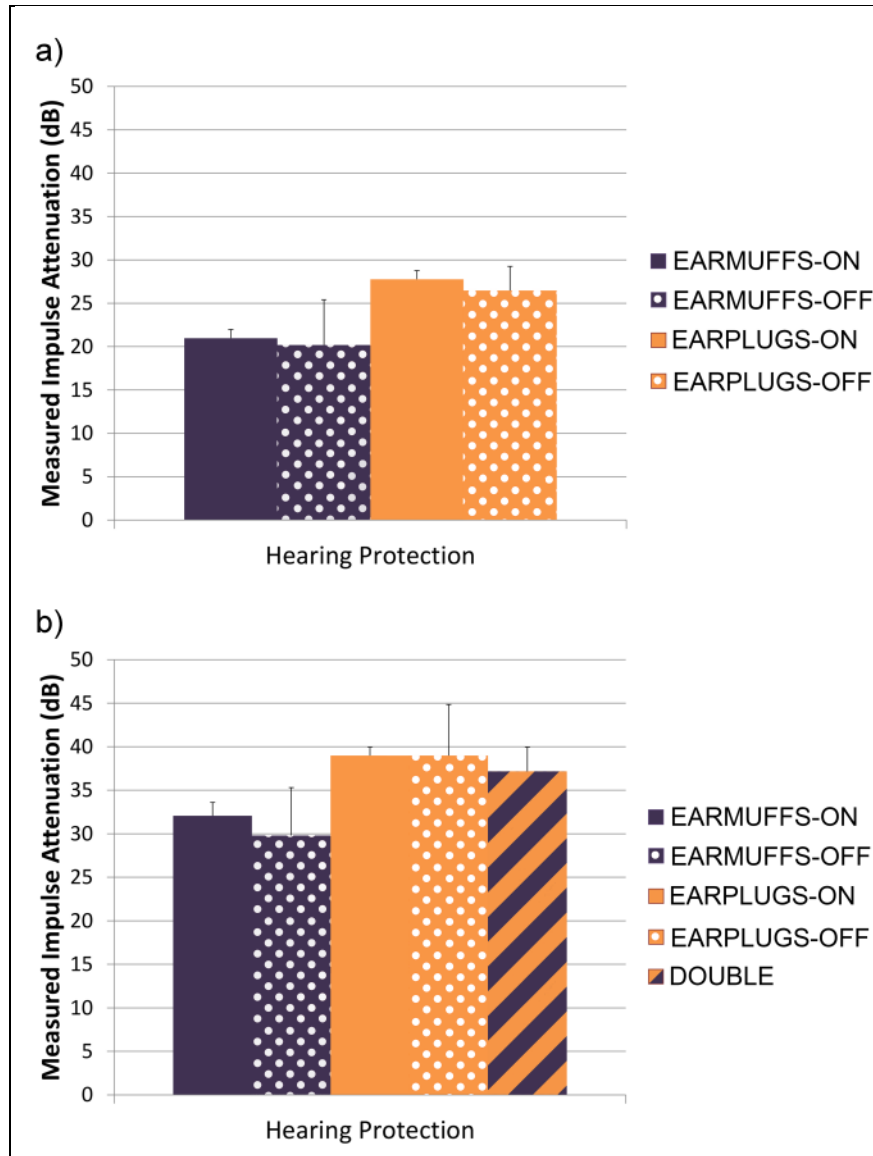
Figure 16. Hearing protector attenuation measured with the SA microphones on and off for (a) 145-dB peak and (b) 160-dB peak impulse signals.

An analysis of variance (ANOVA) was computed for impulse attenuation with the independent variables of HPD condition (EM, EP, and double), presentation level (145- and 160-dB peak), and SA microphone setting (on, off). The significant effects are shown in table 1. The EP and double hearing protection conditions provided about 5 dB more attenuation than EM alone and this main effect was significant, $F(2, 49) = 13.7$, $p < 0.01$. When used with the SA microphones on, the hearing protector passthroughs are clearly shutting off and attenuation is roughly the same as when they are off; there is no significant main effect or interaction for this variable. However, there is an effect of presentation level in that the devices provided as much as 10 dB more attenuation for the higher presentation level and this main effect was significant, $F(1, 49) = 59.7$, $p < 0.1$. This effect has been observed in other measurements of impulse noise protection

(Nakashima et al., 2006); it generally appears that attenuation is nonlinear, increasing somewhat as the impulse level increases.

Table 1. Significant ANOVA results for impulse noise attenuation as a function of HPD condition, presentation level, and SA microphone on/off ($\alpha < 0.05$).

Source of Variance	dF	F	ρ
HPD	2	13.7	0.000
Presentation Level	2	59.7	0.000
Error(corrected)	*49*	*20.1**	

*Mean Squared Error.

3. Localization Testing

The ability to localize sounds was evaluated for the EM, EP, CIPHER, CIPHER + EP, CIPHER without the mandible, INTERCPT, INTERCPT + EP, and INTERCPT without the mandible and compared to the bare head.

3.1 Participants

Twelve listeners were recruited from the population of volunteers aged 18–40 years and 11[*] participated in the testing. Listeners were screened to ensure normal hearing by an experimenter (and under the guidance of an audiologist). Listeners' ears were inspected using an otoscope to ensure that their ear canals were unobstructed and that there would be no interference with the use of EP. Their pure tone thresholds were measured for octave frequencies from 250–8000 Hz using calibrated audiometric equipment in a sound-treated room. All 12 participants had pure tone thresholds no higher than 20-dB hearing level (HL) for all frequencies screened, and thus met the Army's H1 hearing classification, defined in the Army Hearing Conservation Program (DA PAM 40-501, 1998) as an average threshold level at 500, 1000, and 2000 Hz that does not exceed 25-dB HL, with no individual threshold greater than 30-dB HL, and the threshold at 4000 Hz no greater than 45-dB HL. The investigators adhered to the policies for protection of human subjects as prescribed in Army Regulation (AR) 70-25 (1990).

3.2 Facilities and Instrumentation

3.2.1 Loudspeaker Array

Target stimuli were presented from a spherical loudspeaker array consisting of 57 Meyer Sound MM-4XP miniature loudspeakers housed in the Sphere Room of the EAR (Henry et al., 2009). Target sounds were presented from the 16 loudspeakers on the horizontal ring at 0° elevation; the

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[*]One participant's hair was incompatible with the headgear.

loudspeakers are located at equal intervals of 22.5° separation and the radius is approximately 2 m (figure 17).

Figure 17. Testing setup used for the localization test in the EAR's Sphere Room (shown with ACH not used in this experiment).

3.2.2 Rotating Chair

Each participant sat in a rotating chair at the center of the loudspeaker array on a raised platform that placed their ears at the same elevation as the 0° loudspeaker ring. The chair was free to rotate 360° and was equipped with an optical shaft encoder and a laser tracker on the center of a horizontal bar attached to the chair in front of the participant. Although the bar is free to rotate ±90° in pitch, it was fixed in place to allow for responses only from the horizontal plane during this study. Participants began each trial facing 0° azimuth and then responded by rotating the chair to point the laser in the direction from which they believed a stimulus came, pushing a button to register their response. A computer recorded the direction of the response based on the outputs of the laser tracker and the optical shaft encoder, providing redundant positional information. During this study, the laser tracker data were used in the analyses.

3.3 Independent Variables

There were two independent variables investigated in the study: (1) head condition and (2) sound source azimuth. Nine head conditions were evaluated: bare head, earmuffs, earplugs, CIPHER, CIPHER + EP, CIPHER without the mandible, INTERCPT, INTERCPT + EP, and INTERCPT without the mandible. During testing of the EM and EP (and any combination of helmet with EP) the SA microphones were turned on and set to the lowest amplification setting.

There were 16 azimuth locations (0°, ±22.5°, ±45°, ±67.5°, ±90°, ±112.5°, ±135°, ±157.5°, and 180°). A 250-ms burst (with 5-ms linear amplitude ramps) of white noise at 70 dB A was presented from each of the loudspeakers nine times, for a total of 144 instances per block of trials. The order of presentation location was varied randomly within the block. A single block of trials was presented for each of the head conditions.

3.4 Dependent Variables

The dependent variable of interest was azimuth error—defined as the difference in degrees between the perceived stimulus source location azimuth (as identified by the listener) and that of the actual stimulus source azimuth.

3.5 Procedures

After the initial audiometric screening, all participants were familiarized with the listening task prior to initiation of their first block. Each participant was then fitted properly with the appropriate helmet/HPD system. Participants listened to blocks of stimuli that consisted of all trials for a particular head condition. Each block lasted approximately 25 minutes (min). Participants were given breaks between blocks to reduce the effects of fatigue. Additionally, each trial was initiated by the participant, so additional breaks could be taken if needed.

3.6 Data Analysis, Results, and Discussion

Our objective was to measure the effects of the helmet/HPDs on auditory localization ability relative to that with the bare head as a measure of SA. Localization errors made in this study

were calculated as signed (constant) and unsigned azimuth errors. Signed error contains information about both the magnitude and the direction of an error. Average signed error can reveal underlying distortions of the auditory space stemming from the acoustics of the equipment or the test space itself. However, when taken as an average, signed data underestimates overall localization errors because errors in opposite directions cancel each other out. Thus, the average signed errors do not allow us to evaluate judgment precision (random error), which is reflected by the standard deviation of localization responses (Hartmann, 1983). Average unsigned error gives a better estimate of the magnitude of error and precision; therefore, both types of error will be discussed.

Two-factor analyses of covariance (ANCOVA) were conducted for the signed (table 2) and unsigned azimuth (table 3) error with the independent variables being head condition and sound source azimuth. Subject ID was included as a covariate in order to account for individual differences. Polar plots of the signed errors as a function of the TCAPS/helmet worn and the sound source azimuth were also calculated (figure 18).

Table 2. Significant ANOVA results for signed azimuth error ($\alpha < 0.05$).

Source of Variance	dF	F	P
Azimuth	15	29.7	0.000
Head Condition × Azimuth	120	11.1	0.000
Error	*10621*	*1991.92*	

Table 3. Significant ANOVA results for unsigned azimuth error ($\alpha < 0.05$).

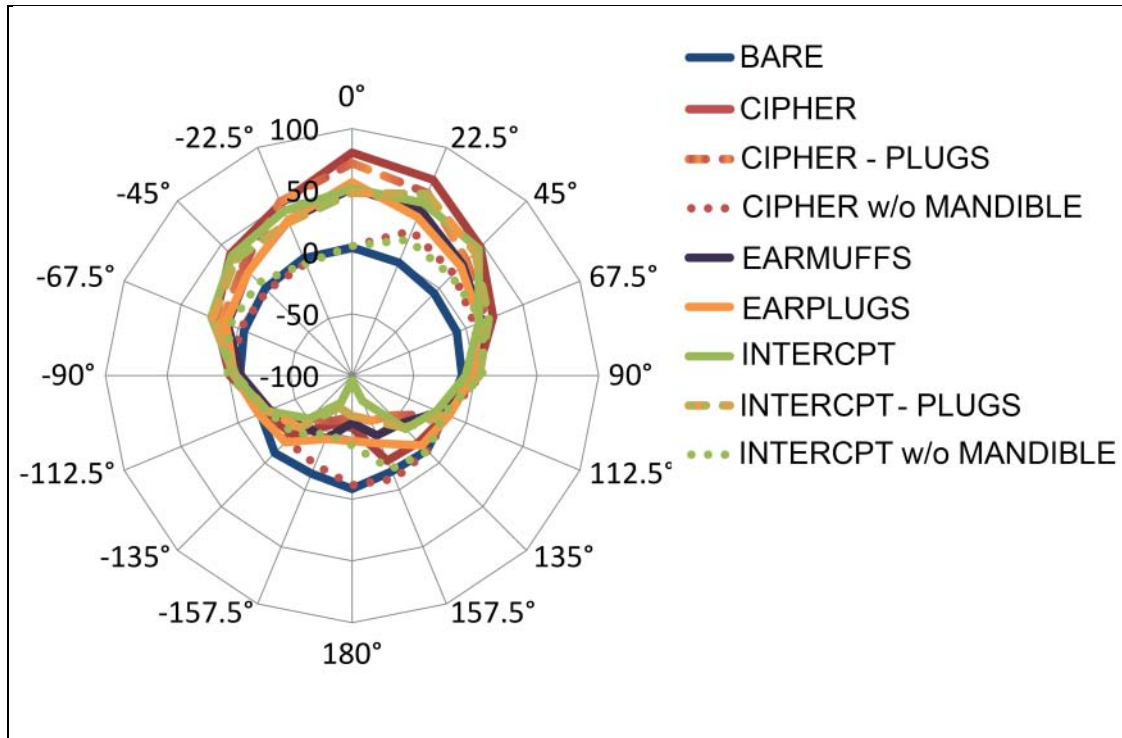| Source of Variance	dF	F	P
Head Condition	8	24.6	0.000
Azimuth	15	10.5	0.000
Head Condition × Azimuth	120	5.5	0.000
Error	*10621*	*1724.5*	

Figure 18. Signed azimuth error as a function of sound source azimuth for all conditions. Labels indicate degree azimuth. Concentric rings indicate error. Bare indicates the bare head, without helmet, or HPD.

In the signed error data, negative errors indicate the subject estimated the sound source estimate was closer to the front (0°), than the actual target location. Positive errors mean that the estimate was farther to the rear than the actual target location. If localization errors are driven by lack of precision, estimates will fall on either side of the target location and on average cancel out. Using average signed data will obscure any real differences in the magnitude of errors occurring for the various helmets. This is not to suggest that all errors are likely to be cancelled out. Differences due to an increase in front-back confusions will result in an increase in positive errors near 0° and an increase in negative errors near 180°. Even with no headgear present, it is normal to observe some differences in error as a function of azimuth, due to front-back confusions.

Wearing a helmet/HPD altered one's ability to localize sounds. This main effect was significant, $F(15, 10621) = 29.7$, $p < 0.01$. The effect of helmet/HPD use varies significantly as a function of azimuth and this interaction was significant, $F(120,10621) = 11.1$, $p < 0.01$. In figure 18 it can be seen that wearing hearing protection and wearing the helmets with the mandibles attached increased positive errors in the front near 0°, and increased negative errors in the rear near 180°, consistent with what would occur as a function of increased front-back confusions. Wearing the helmets with the mandibles detached reduced signed errors; for many angles performance was similar to the bare head condition.

The signed error data allows us to detect any biases that signal problems with the measurement method or acoustics of the facility. The data shown here for the hearing protectors and the bare head are symmetric relative to the midline. There are some small differences between the left and right hemispheres for the conditions in which a helmet was worn, most notably at about 22.5°. This suggests that there is some form of asymmetry in the effect of the helmet on the pathway of sound to the ears. This may have been true—as the helmets were difficult to fit well, and tended to rotate off center (see figure 19).

Figure 19. CIPHER helmet as worn by a volunteer. Note that
the helmet tended to rotate off center.

Figure 20 shows the average unsigned error for (a) helmets and (b) HPDs. For comparison, note that during a recent study of localization performance with the ACH, conducted in the same facility (Scharine, in preparation)[*] resulted in average unsigned azimuth error of 24.5° for the ACH and 17.2° for the bare head. When worn without the mandibles attached, unsigned azimuth error with the CIPHER (14°) and INTERCPT (19°) helmets is not statistically different ($\alpha < 0.05$) from that for the ACH. There was a significant main effect of head condition [$F(8, 10621) = 24.6$, $p < 0.01$]. Planned comparisons showed that the differences between the bare head and all of the helmet/HPD conditions were significant [$F(8, 10621) = 135.4$, $p < 0.01$], with the exception of the CIPHER worn with the mandible detached ($p = 0.623$). Although there was a significant difference between the two helmets if worn with the mandibles ($p < 0.01$), there

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[*]As of this writing, the report of the ACH data mentioned here is still in the writing stage but details may be requested from the author. It should also be noted that the observed unsigned azimuth error for the bare head during this study was 12°, suggesting that the participants of this study were slightly better at localizing sounds.

were not significant differences otherwise ($p_{+ EP}$ = .687; $p_{without mandibles}$ = 0.242). Wearing EM caused, on average, 7.4° more localization error than wearing EP ($p < 0.01$). Unsigned localization error was largest for the INTERCPT (with mandible); this was significantly larger than the error measured for the EM. However, whether this is of practical significance is questionable. The expected main effect of sound source azimuth was significant [$F(15, 10621) = 10.5, p < 0.01$]. The interaction between head condition and azimuth was also significant [$F(120, 10621) = 5.5, p < 0.01$]. Figure 21 shows the unsigned azimuth error as a function of azimuth for the (a) helmets and (b) HPDs/helmets. For graphing purposes the data are shown collapsed across the midline; the full data set is shown in table 4. The main effect of azimuth can be seen in the general tendency for errors to be larger near 0° and 180°. The effect of azimuth on unsigned error values observed for the bare head and for the helmets worn without their mandibles is fairly similar. When the mandibles are added, the increase in the magnitude of errors near 0° and 180° is clearly significant.

An analysis of errors due to reversals was done by computing whether the reverse of an estimate was closer to the sound source location than the estimate. If it was, the trial was coded as a reversal. Figure 22 shows the percentages of trials coded as a reversal for each head condition and as a function of azimuth for the (a) CIPHER and (b) INTERCPT conditions. It is clear from the graphs that errors due to reversals drive most of the differences in localization performance. Worn alone, the INTERCPT helmet seems to affect localization slightly more than the CIPHER helmet, but worn with the EP this difference vanishes. The mandibles significantly increase localization error; however, this effect is only slightly more than the effect of the EP worn alone and not significantly more than the EM alone.
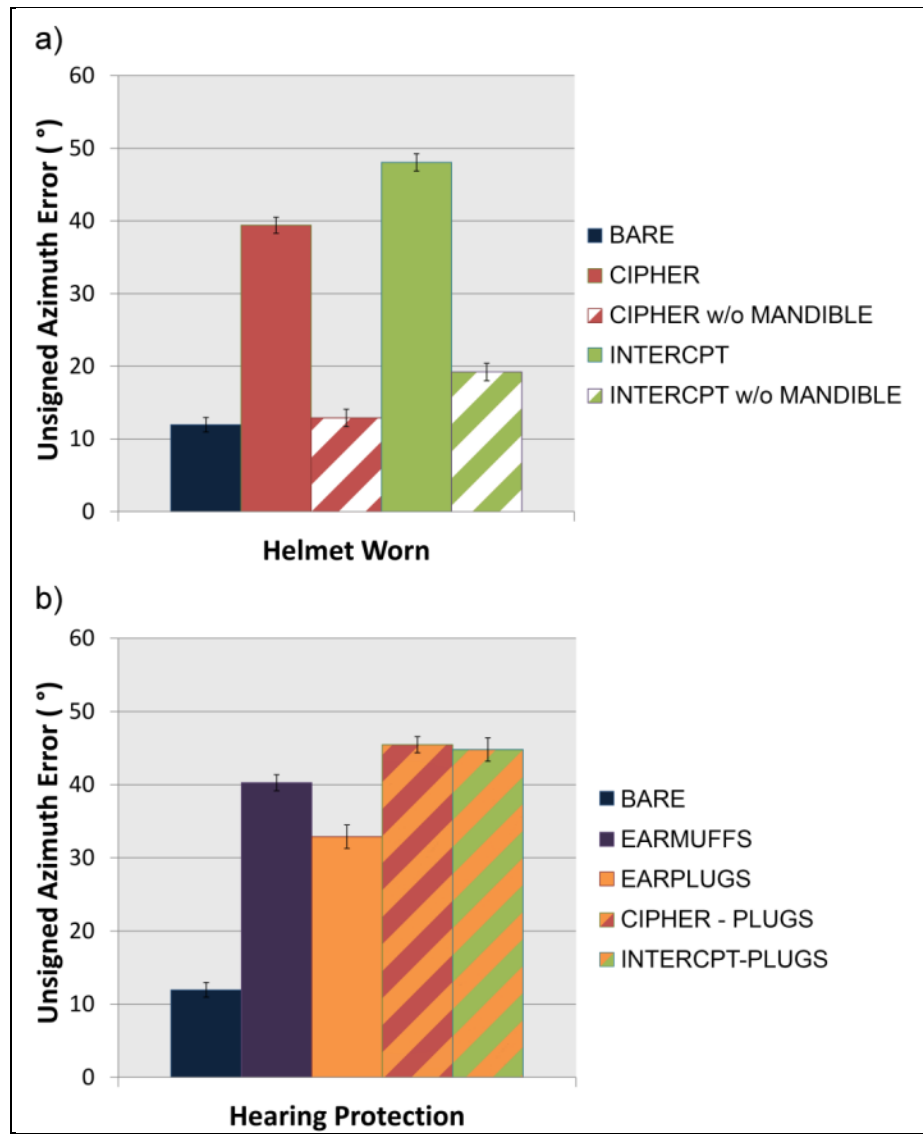
Figure 20. Unsigned azimuth error for the (a) helmet and (b) HPD conditions. Error bars represent ±1standard deviation.
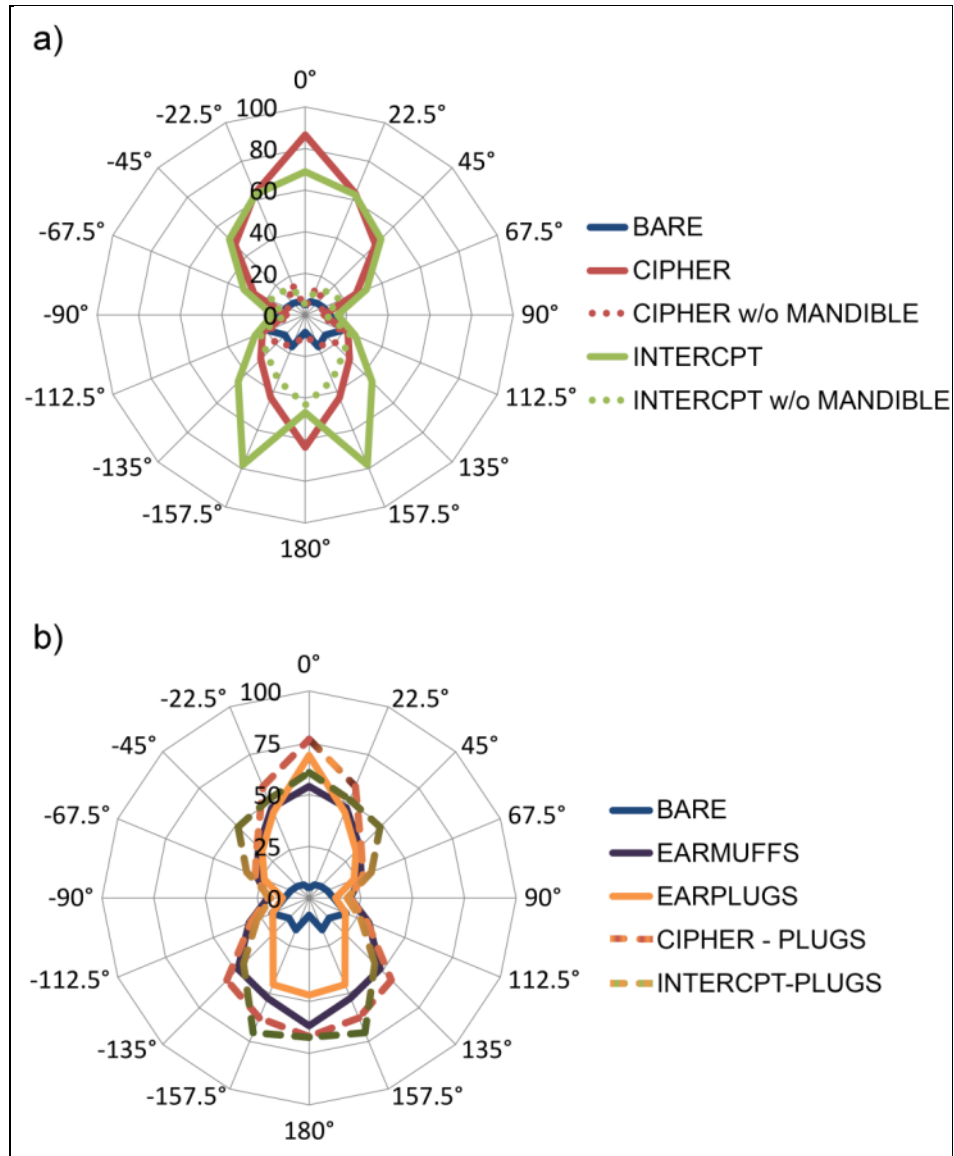
Figure 21. Unsigned azimuth error as a function of source azimuth (polar axes) for the (a) helmet and (b) HPD conditions.

Table 4. Average unsigned error values and standard deviations for each head condition by azimuth.

Average Unsigned Azimuth Error (degrees)

	Bare	CIPHER	CIPHER w/Plugs	CIPHER w/o Mandible	EM	EP	INTERCPT	INTERCPT w/Plugs	INTERCPT w/o Mandible
0°	5	86	77	5	54	69	66	61	5
22.5°	6	74	62	30	50	52	59	61	21
45°	7	52	38	21	41	39	57	54	18
67.5°	11	28	30	14	32	23	33	32	20
90°	13	10	24	10	24	15	19	22	11
112.5°	19	21	32	17	32	18	27	26	21
135°	15	27	60	14	51	24	40	45	18
157.5°	17	27	63	12	55	44	80	67	19
180°	8	63	67	11	62	47	96	67	43
−157.5°	16	58	62	22	50	47	76	74	49
−135°	12	33	53	28	46	25	51	45	35
−112.5°	20	23	28	21	30	20	26	28	26
−90°	10	8	15	8	16	11	12	15	9
−67.5°	8	25	26	6	23	23	31	33	16
−45°	9	43	33	4	28	26	46	43	14
−22.5°	8	52	55	2	44	38	66	41	2

Standard Deviation of Unsigned Azimuth Error (degrees)

|	Bare	CIPHER	CIPHER w/Plugs	CIPHER w/o Mandible	EM	EP	INTERCPT	INTERCPT w/Plugs	INTERCPT w/o Mandible
0°	24.8	84.5	83.8	26.4	77.1	79.0	82.2	78.6	26.3
22.5°	17.1	64.6	63.1	56.2	62.8	59.2	63.7	65.1	48.3
45°	5.7	42.4	40.6	36.4	41.9	40.6	41.0	44.3	33.5
67.5°	13.5	21.9	22.7	20.3	21.9	18.9	19.3	25.8	23.5
90°	12.4	8.8	24.0	9.7	15.3	13.1	12.0	16.0	10.6
112.5°	16.3	17.4	30.7	17.1	24.8	14.2	20.7	21.7	14.9
135°	14.6	27.7	46.5	26.7	40.9	28.7	38.6	37.0	27.3
157.5°	22.7	45.9	64.3	34.6	62.0	56.7	61.5	61.4	42.8
180°	17.5	79.9	81.4	22.9	72.8	65.1	83.7	82.3	71.7
−157.5°	20.3	56.6	62.0	32.7	55.6	56.0	58.6	61.0	54.3
−135°	13.9	30.7	42.3	24.7	38.2	33.7	36.5	37.9	31.4
−112.5°	16.0	14.1	19.0	13.8	17.1	13.7	14.6	21.2	19.7
−90°	8.9	9.3	11.5	9.3	14.6	11.3	15.1	12.7	9.3
−67.5°	7.3	19.2	18.9	7.8	21.7	17.8	22.6	21.4	16.2
−45°	16.7	42.7	35.8	4.8	32.1	32.9	39.8	42.0	27.7
−22.5°	24.5	63.6	61.5	2.8	57.1	53.0	62.4	60.9	2.9

31
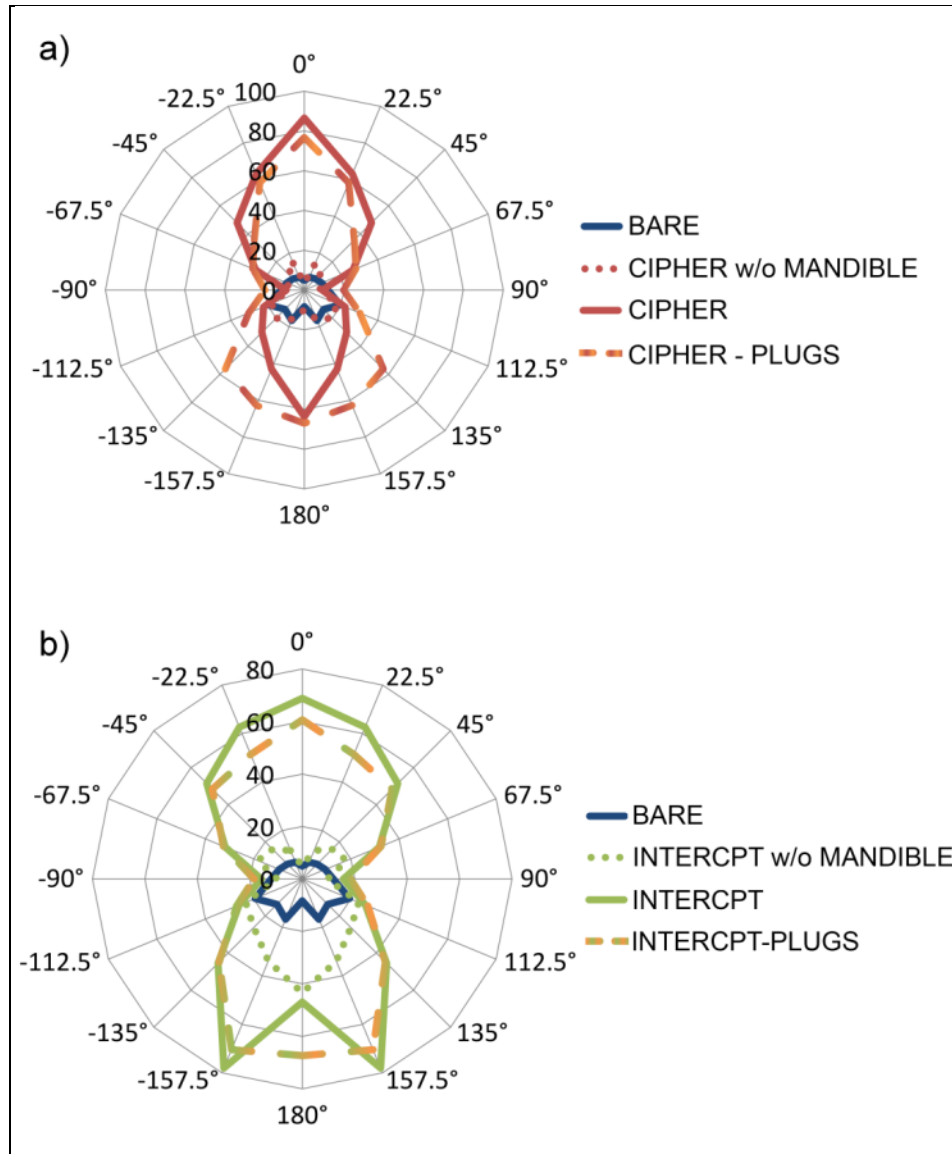
Figure 22. Unsigned azimuth error as a function of source azimuth for the (a) CIPHER and (b) INTERCPT helmet conditions.

4. Speech Intelligibility Testing

Intelligibility of speech, as transmitted through the SA microphones, was assessed for three presentation levels. All testing was completed with the SA system active and with the amplification set to on-low.

4.1 Participants

Six listeners aged 18– 40 years were recruited for participation in the speech intelligibility assessment. The same criteria for hearing were used as for the localization measures.

4.2 Facilities and Instrumentation

Target stimuli were presented from one of three Genelec 8030 loudspeakers located in the Listening Laboratory of EAR. Each loudspeaker was placed at a 1-m distance from the listener. Levels were calibrated by presenting a single-syllable speech item from the Modified Rhyme Test (MRT) speech corpus "band," and presenting it repeatedly (in a "loop") without any silent interval. Each loudspeaker was calibrated to a different level so that one loudspeaker was presenting at 50 dB A, another at 60 dB A, and the third at 70 dB A. Calibration was achieved by playing the voiced portion of one of the test items as a loop, and measuring that level with the SLM.

A laptop computer was used to trigger speech items and to record listener responses.

4.3 Speech Corpus

The speech items used were from the MRT (House et al., 1963). This test consists of six lists of 50 monosyllable English words. It is constructed from 50 sets of six words, such that all words in a set differ only in their beginning or ending consonant. For each trial, a word is presented and the listener is asked to select the correct word from the six words in that set. The six 50-item lists are constructed by selecting one of the six words from the rhyming sets, without repetition, so that each list is roughly equivalent in difficulty. A single 50-item list was presented for each of the head/presentation level conditions described in the next section. Items within the list were presented in random order. Because there were nine head/presentation levels, three of the lists were used for two conditions. The order of the head conditions and the assignment of lists to each head/level condition were randomly counterbalanced and differed for each participant.

4.4 Independent and Dependent Variables

There were two independent variables investigated, head condition and presentation level. The dependent variable, percent correct speech recognition, was measured for three head conditions (EM, EP, and bare headed) at each of three presentation levels (50, 60, and 70 dB A).

4.5 Procedures

After the initial audiometric screening, a five-item demonstration was used to familiarize all listeners with the task. Responses were made by clicking on the corresponding item from the words presented on the screen. Following familiarization, the participant was fitted with a headset (or no headset for the bare head condition) and then presented with the first block of trials. For each head condition, blocks were presented at 50, 60, and 70 dB A. Then the next headset was fitted and the process repeated. Each list required approximately 5 min for

completion and participants were encouraged to take rest breaks between lists to minimize fatigue.

4.6 Results and Discussion

Percent correct* word recognition is shown for each of the conditions in figure 23. Performance was near perfect for all conditions and levels, and there were no significant differences across conditions. In part, this is not surprising, because testing was conducted in quiet and there was some amplification by the headsets. If future versions of this system are to be evaluated, it is suggested that they be evaluated in noise to more fully characterize their performance.
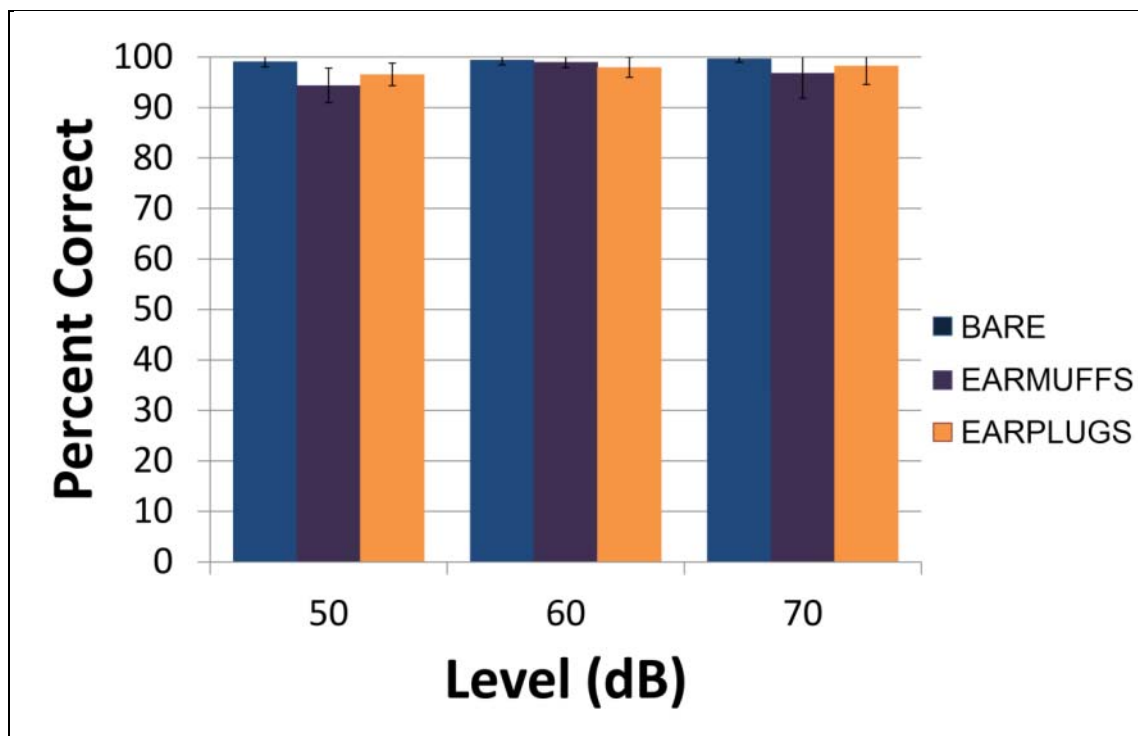

Figure 23. Percent correct speech recognition on MRT as a function of signal level. SA microphones were turned on and set to the default (middle) level. All testing was done in quiet.

5. Summary and Conclusions

Two candidate HEaDS-UP helmet systems (CIPHER helmet, INTERCPT helmet, and mandibles), and their accompanying SELEX tactical communications headset options (EM, EP, and combined double protection), were evaluated for their effects on auditory SA. Since the

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*It is not uncommon for percent correct speech recognition data to be transformed to correct for the fact that the response sets are closed sets and there is an upper bound to possible scores (100%). This is done to ensure that the data do not violate assumptions of normalcy that are required for statistical analyses. However, since there do not appear to be any *practical* differences requiring statistical verification, the data are presented here unaltered.

systems are modular and reconfigurable, they were evaluated in all relevant configurations, with the exception of the helmet worn with the EM.*

Measures of the directional attenuation of steady-state noise documented spectral changes as a function of helmet and hearing protection use. Only minor overall attenuation (approximately 4 dB A) was observed for the helmets worn alone, and attenuation greater than 30 dB A was observed for all of the helmet/HPD conditions. Directional effects were observed in the spectral profiles of the recordings made for each helmet/HPD condition.

Measurement of the input-output function of white noise presented at 5-dB increments from 70–105 dB A for HPDs in three active settings (off, on-low, and on-high) suggest that the headsets begin to limit the transmission of the SA microphones when the ambient levels reach about 85 dB A, but that the amplification settings determine the actual level transmitted to the ear. When the SA microphones are turned on-high, they provide about 20 dB of amplification. For the high-amplification setting and due to no passive attenuation of ambient noise, levels reached 115 dB A under the EM for ambient levels of 105 dB A.

The HPD systems (both EM and EP) provided impulse noise protection equivalent to that of passive protection when the SA microphones were on and amplification was set to on-low. Impulse attenuation increased as the level of noise increased.

Measures of the systems' effects on sound localization suggest that the addition of mandible protection reduces one's ability to localize sound, but that this effect is not much greater than that of wearing EM. As always, sound localization ability is greatest when the ears are unoccluded; it is recommended that when mandible protection is not required that it not be worn. EP are preferable to EM in terms of their effect on auditory localization. The combination of EM and helmet was not tested due to issues with fit. This testing is planned for Phase IV. The CIPHER helmet when worn alone did seem to have some advantage over the INTERCPT helmet,† but it is unclear whether this is of practical significance.

Finally, speech intelligibility of the HPD systems when worn with the SA microphones active suggests that in quiet conditions, detection and recognition of speech is unaltered relative to unaided hearing. As tested here, the SA system performed adequately. Phase IV testing will evaluate speech in noise and at different gain settings to determine if there is any impairment in more challenging acoustic environments.

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*Because these systems were prototypes, EM did not fit most participants under the helmets. This configuration will be tested in Phase IV.

†We make the anecdotal observation that headgear with nonspherical features (versus smooth round surfaces) seem to have a slight advantage for localization; their small physical features may provide disambiguating cues. This pattern was observed for the unpublished CB-GSS test data of chemical biological face protection as well.

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Appendix. Additional Localization Testing: INVISIO Study

After the testing documented in this report, we were asked to test an additional HPD headset, the Television Equipment Associates, Inc. (TEA) INVISIO* X5 ITE headset paired with the X50 control unit (X5) (figure A-1). This testing was included as a condition with another test that included several versions of Peltor ComTAC TCAPS headsets.† In order to specify the source of the data, we shall refer to the testing discussed in the main body of this report as the HEaDS-UP (HU) study and data collected during the Peltor ComTAC testing as the INVISIO study. In order to give context to performance with the X5 headset, we will include the EP data (collected during the HU study) as well as data collected with the head bare (during both the INVISIO and the HU studies).

Figure A-1. TEA INVISIO X50 control unit and X5 ITE headset.

A.1 Participants: INVISIO Study

Twelve listeners were recruited from the population of volunteers aged 18–40 years. The criteria for participation were identical to that of the HU study.

A.2 Procedures and Facilities: INVISIO Study

The participants used the same test facility, response method, and loudspeaker array as for the HU study. The target stimulus and number of stimulus trials per block (144) were also the same. After the initial audiometric screening, all participants were familiarized with the listening task and fitted properly with the appropriate headgear. They then completed a single block of trials (9 repetitions for each of the 16 locations) for each of the headgear conditions under test.

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* INVISIO is a registered trademark.
†This report was submitted as a technical report and the number should be available prior to publishing this report.

A.3 Variables

The dependent variable of interest was azimuth error (defined in section 3.4 of this report). As before, there were two independent variables: (1) head condition and (2) sound source azimuth. The INVISIO head conditions were: bare head (INVISIO) and X5. The SA microphones were turned on and set to the lowest amplification setting for the X5. (This was also true for the EP condition in the HU study.) In the data analysis, there will be four conditions: bare head (INVISIO), bare head (HU), X5, and EP.

A.4 Data Analysis, Results, and Discussion

Our objective was to measure the effects of the X5 on auditory localization ability. Localization errors, calculated as the absolute difference between the sound source azimuth and the reported azimuth, are reported here as unsigned azimuth errors. During the INVISIO study the data from the optical shaft encoder* were used for the analyses; whereas, during the HU study, the tracker data were used.

The participants in the two studies were different. Since there are individual differences in underlying localization ability, both sets of bare head data are reported here as a reference. There were differences between the two groups in terms of localization performance with a bare head; the average unsigned error was 12° for the HU study participants, and 7° for the INVISIO study participants.

The average unsigned error for each of the HPD conditions and as a function of horizontal azimuth (collapsed across the midline) are presented in figures A-2 and A-3.

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*Ideally the response chair provides redundant horizontal azimuth data from both the optical shaft encoder and the response tracker. Unfortunately, during the HU testing, the optical shaft encoder became disconnected, so only the tracker data were available. During the INVISIO study, both were operational.
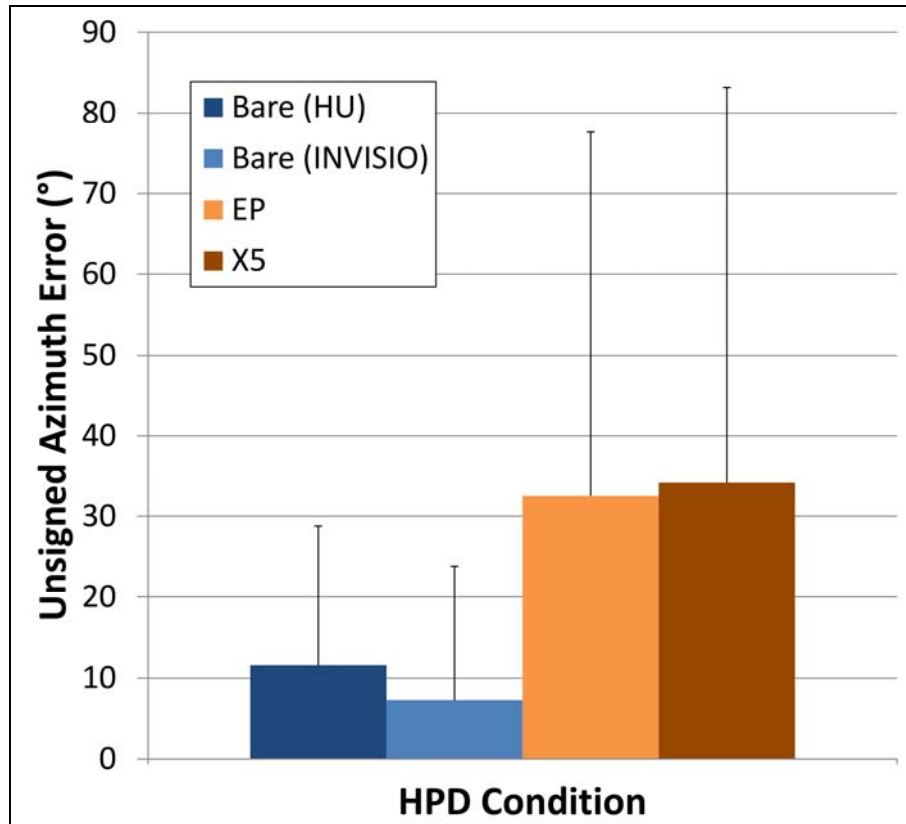
Figure A-2. Average unsigned azimuth error observed for the test conditions. Error bars indicate +1 standard deviation.
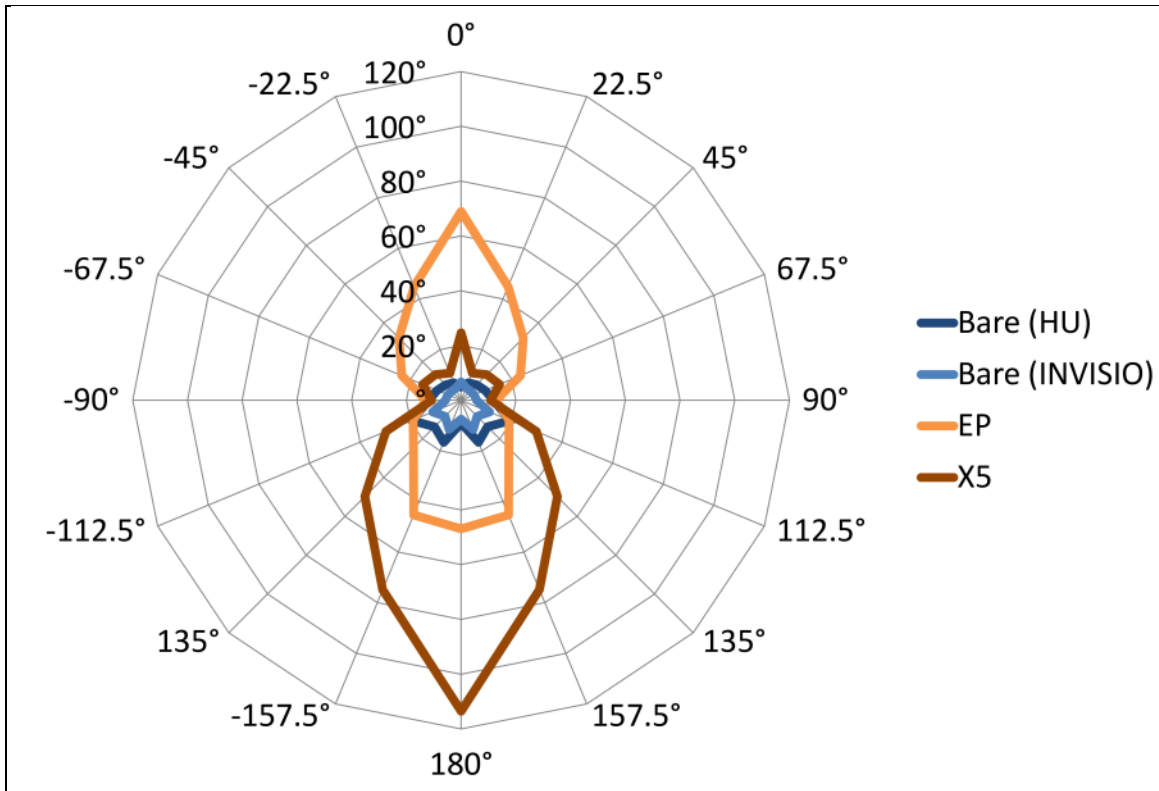
Figure A-3. Polar plot of unsigned azimuth error observed for the test conditions as a function of horizontal azimuth.

A two-factor ANCOVA was conducted on the combined data set with head condition and sound source azimuth as the independent variables. Subject ID was included as a covariate in order to account for the individual differences noted previously. Not surprisingly, there were significant main effects for HPD and azimuth, $[F(3, 6402) = 324.8, p < 0.01; F(15,6401) = 43.2, p < 0.01]$. Their interaction was significant, $[F(45, 6402) = 29.6, p < 0.01]$.

Planned contrasts were used to test whether there were significant differences between the two groups of participants, and whether the two HPDs affected localization ability differently. The bare headed performance of the two groups of participants was not significantly different ($p = 0.23$); there was also no significant difference between performance with the two HPDs ($p = 0.09$). The source of the significant main effect of head condition is the significant difference (an average increase in unsigned azimuth error of 48°) between localization with a bare head versus localization with an HPD ($p < 0.01$).

Inspection of unsigned azimuth error as a function of azimuth shows that wearing the X5 resulted in large unsigned azimuth error at angles near 180° in comparison to wearing the EP. Conversely, wearing the EP resulted in larger unsigned azimuth error values for angles near 0°, but the difference between front and rear was less pronounced. Localization errors near 0° and 180° are dominated by front-back confusions because binaural information is ambiguous with regard to discrimination of front from rear. The use of headgear, such as HPDs and helmets,

distorts monaural cues used to disambiguate binaural information; therefore, it can be argued that most differences in auditory localization ability resulting from headgear use are due to increased front-back confusions. Front-back confusions are not necessarily symmetric. A participant, given ambiguous information, may perceive the sound as originating from the reversed hemisphere randomly, or demonstrate a bias for either the front or back hemisphere. Thus, the increased tendency to perceive sounds as originating from the front suggested by the large errors near 180° for the X5 may simply mean that this particular group of participants preferred the front hemisphere. Similarly, the more balanced pattern for the EP may simply mean that listeners were less biased for the front versus the rear.

Therefore, the question is whether there is a difference in the overall tendency to make errors that are due to reversals, rather than the specific direction of the errors themselves. To test this, the errors were coded to identify those resulting from front-back reversals in the same manner described in section 3.6 (last paragraph). As before, a two-factor ANCOVA was computed for the dependent variable of reversals, with head condition and sound-source azimuth as the independent variables and subjects as the covariate. Similarly, there were significant main effects of head condition and presentation azimuth, $[F(3, 6402) = 273.4; p < 0.01; F(15, 6402) = 62.2, p < 0.01]$. The interaction of head condition and presentation azimuth was also significant, $[F(45, 6402) = 18.5, p < 0.01]$. A planned comparison of the number of reversals observed for the X5 and the EP headsets showed no significant difference ($p = 0.914$). Thus, it can be stated that statistically, *there is no evidence that the two headsets affect localization ability differently.*

List of Symbols, Abbreviations, and Acronyms

ACH   Advanced Combat Helmet

ANCOVA   analysis of covariance

ANOVA   analysis of variance

AR   Army Regulation

ARL   U.S. Army Research Laboratory

ATF   Auditory Test Fixture

CIPHER   Conformal Integrated Protective HEadgeaR

dB   decibel

dB A   decibels A-weighted

EAR   Environment for Auditory Research

EM   earmuffs

EP   earplugs

h   hour

HEaDS-UP   Helmet Electronics & Display System-Upgradeable Protection

HL   hearing level

HPD   hearing protection device

HU   HEaDS-UP

in   inch

INTERCPT   ITEgRated Conformal Protective helmeT

ISL   Institute of Saint-Louis

ITE   in-the-ear

m   meter

MIL-STD   Military Standard

min   minute

MRT	Modified Rhyme Test
NIOSH	National Institute for Safety and Health
NRR	noise reduction rating
OSHA	Occupational Safety and Health Administration
PINS	pneumatic impulse noise source
s	second
SA	situation awareness
SLM	sound level meter
SPL	sound pressure level
TEA	Television Equipment Associates, Inc.
TCAPS	tactical communications and protection system

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